Geomorphology 248 (2015) 344–362

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Controls on modern tributary-junction alluvial fan occurrence and morphology: High Atlas Mountains, Morocco

Martin Stokes *, Anne E. Mather

School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, Devon PL4 8AA, UK

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 3 August 2015
Accepted 4 August 2015
Available online 8 August 2015

Keywords:
Alluvial fan
Tributary junction
Flood discharge
Coupling
Connectivity

ABSTRACT

Modern tributary-junction alluvial fans (cone-shaped depositional landforms formed in confined valley settings) were analysed from a 20-km-long reach of the Dades River in the distal part of the fold-thrust belt region in the south-central High Atlas Mountains of Morocco. Here, a deeply dissected network of ephemeral tributary streams and a perennial trunk drainage characterised by an arid mountain desert climate are configured onto a folded and thrust faulted Mesozoic sedimentary sequence. Out of 186 tributary streams, only 29 (16%) generated alluvial fans at their tributary junctions. The fan-generating catchments possess higher relief, longer lengths, lower gradients, and larger areas than nonfan-generating catchments. Whilst geologically, fan-generating catchments are underlain by folded/steeply dipping weak bedrock conducive to high sediment yield. Tributary-junction fans are built from debris flow or fluvial processes into open or confined canyon trunk valley settings. The proximity of the perennial trunk drainage combined with the valley morphology produces lobate or foreshortened trimmed fan forms. Analysis of fan (area, gradient, process), catchment (area, relief, length, gradient), and tributary valley (width) variables reveals weak morphometric relationships, highlighted by residual plots that show dominance of smaller and lower gradient than expected fan forms. These morphometric relationships can be explained by interplay between the catchment and trunk drainage geology, morphology, climate, and flood regime that are combined into a conceptual 'build and reset' model. Ephemeral tributary-junction fans develop progressively during annual localised winter-spring storm events, attempting to build towards a morphological equilibrium. However, the fans never reach an equilibrium morphological form as they are reset by rare (>10 year) large floods along the River Dades that are linked to regional incursions of Atlantic low pressure troughs. The model highlights the spatial and temporal variability of tributary-junction fan building and illustrates the connectivity/coupling importance of such features in dryland mountainous terrains.

1. Introduction

Alluvial fans are cone-shaped depositional landforms that form at mountain fronts or tributary junctions, reflecting different confinement settings (Harvey, 1997). Research on mountain front fans has commonly investigated morphometric relationships between the catchment and alluvial fan, showing a linkage between morphological components and the processes that shape them (Bull, 1977). Morphometric relationships (e.g., fan area/gradient vs. catchment area) are typically strong for mountain front fans (Harvey, 1997) but are less clear for fans at tributary junctions (Al-Farraj and Harvey, 2005). This reflects the different confinement settings, and especially so at tributary junctions where fan formation and modification is governed by an interaction between (i) geological and morphological characteristics of the tributary catchment and the trunk valley, (ii) the trunk valley space for fan sedimentation, (iii) the sediment–water discharge relationships between the tributary and the trunk drainage, and (iv) the proximity of the trunk drainage to the tributary-junction fan (Wang et al., 2008).

Tributary-junction fans are common in mountainous terrains where rates of sediment supply are high. Valley width and morphology in these settings are important for confinement. Glacially excavated *u*-shaped valleys or fault-controlled valley margins with a subsiding valley floor can produce wide valleys leading to unconfined fan development akin to mountain front settings (Leeder and Mack, 2001; Crosta and Frattini, 2004). Thus, true tributary-junction fans are probably those associated with narrower, *v*-shaped trunk valleys (canyons) that are more often related to nonglaciated valleys and/or associated with active regional tectonic uplift (Wells and Harvey, 1987; Wang et al., 2008). Key examples of research in such areas has explored the presence or absence of fans at tributary-junctions (Gómez-Villar et al., 2006; Wang et al., 2008) and the relationship between tributary-junction fan morphology and simple catchment characteristics (Al-Farraj and Harvey, 2005; Gómez-Villar et al., 2006; Wang et al., 2008). The importance of catchment geology is highlighted in all of these studies in terms of sediment yield to the tributary-junctions and the dominant alluvial fan sedimentary process (e.g., fluvial vs. debris flow). However, catchment

* Corresponding author.
E-mail address: mstokes@plymouth.ac.uk (M. Stokes).

http://dx.doi.org/10.1016/j.geomorph.2015.08.003
0169-555X/

geology is typically treated in a simplified manner, commonly based upon spatially dominant stratigraphic formation lithologies derived from large-scale regional geological survey maps without directed field observation/measurement. Such approaches can lack sufficient consideration of rock strength and the role of catchment geology structure and stratigraphy for sediment yield. Rock strength relates to lithology and fabric (e.g., Goudie, 2006) that collectively influences catchment morphology, hillslope/catchment channel erosion rates, and the size of sediment being supplied to the fan (Hooke and Rohrer, 1977; Calvache et al., 1997). The structural and stratigraphic configuration of bedrock within the catchment can further influence catchment morphology, but importantly it can enhance or suppress catchment slope-channel coupling and catchment throughput, thus affecting sediment supply to the alluvial fan and the processes on the fan (Harvey, 2002a).

Here, we explore the controlling factors for the occurrence and morphological characteristics of modern tributary-junction alluvial fans and their catchments from the distal fold-thrust belt region of the Dades River (south-central High Atlas Mountains, Morocco: Fig. 1) using an integrated remote sensing and field approach. The High Atlas is a tectonically active collisional mountain belt system along the northwestern margins of the Sahara Desert (Fig. 1). Uplift linked to ongoing plate collision has formed a deeply dissected drainage network incised into folded Mesozoic sediments. Despite high relief of 2 to 4 km, Quaternary glacier activity was highly localised (Hughes et al., 2011), thus lacking impact on river valley morphology in the study area with a dominance of *v*-shaped forms linked to a dominance of fluvial and hillslope processes. Winter storms and spring snow melts provide continuous river flow in the highest order trunk drainages, but all other lower order tributary streams are ephemeral (Schulz et al., 2008; Dłużewski et al., 2013). It is the lower order tributary streams that generate catchment sediment that is transported to the highest order trunk drainage (River Dades), where a tributary-junction alluvial fan might develop.

Not all catchments generate tributary-junction fans along the River Dades, so a first objective is to explore this relationship in terms of the upstream catchment (area, sediment storage, and geology) and the downstream trunk drainage valley (morphology, discharge, etc.). Where tributary-junction fans occur, the relationship between the fan shape and trunk valley characteristics (valley shape, width, and proximity to the main river active channel) is explored. The tributary-junction fans and their catchment and trunk valley morphometric properties are then explored using linear regression and analysis of residuals. A conceptual model is then developed to explain the relationship between fan catchment, the tributary valley, and modern climate-related local and regional flood regime characteristics. Collectively, this approach makes an important contribution to the understanding of the coupling/connectivity roles of tributary junction fans as part of the sediment/geomorphic system (e.g., Harvey, 2002a). It achieves this from a spatial perspective but also provides temporal insights into how variations in flood frequency and magnitude can have important impacts upon coupling/connectivity, especially in desert mountain landscapes.

2. Study area background

The study area forms part of the River Dades along the southern flanks of the south-central High Atlas Mountains of Morocco in NW Africa (Fig. 1). Here, the High Atlas is configured into an intracontinental orogenic system formed by Cenozoic suturing between the North African and Eurasian plate margins (Dewey et al., 1989; Frizon de Lamotte et al., 2008). The study area is located along the distal edge of the fold-thrust belt region of the mountain chain, an area dominated by Mesozoic rift basin sediments (Carte Géologique du Maroc, 1985). Alpine tectonics inverted the rift basin resulting in thrust faulting/folding and creation of the High Atlas mountain topography with relief varying from 2 to 4 km (Beauchamp et al., 1999; Teixell et al., 2003). The timing and mechanisms for relief generation are widely debated but recent work using river long profiles suggests that the origins of the modern drainage network can be linked to enhanced Plio-Quaternary uplift (Boulton et al., 2014). However, modern seismicity is infrequent and of

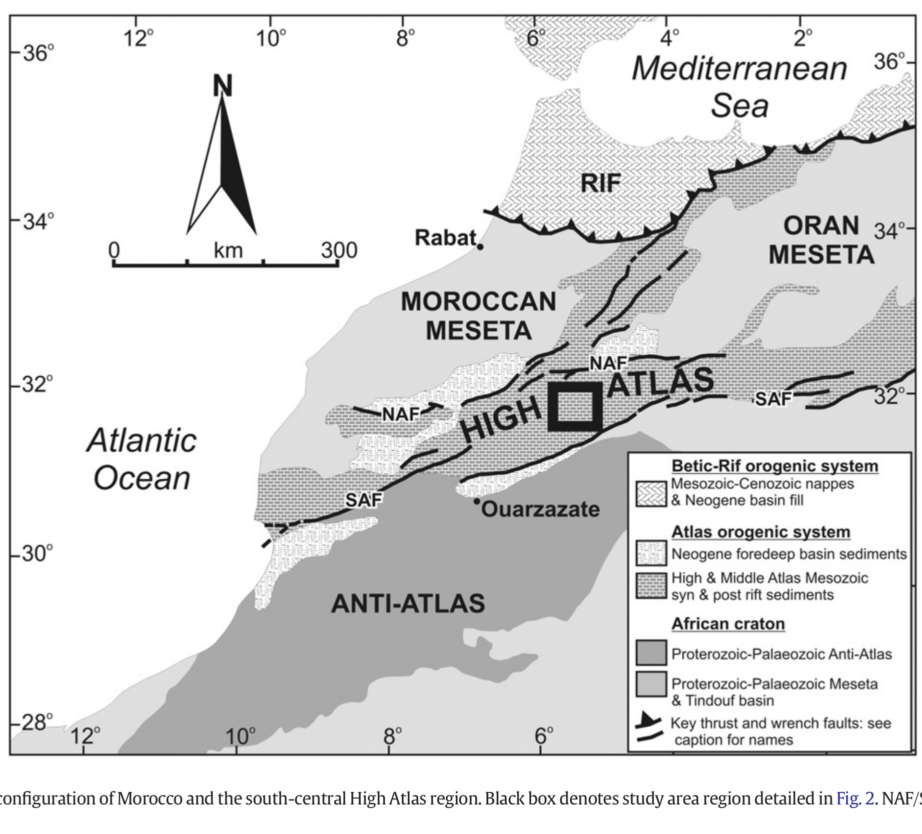


Fig. 1. Tectonic and geological configuration of Morocco and the south-central High Atlas region. Black box denotes study area region detailed in Fig. 2. NAF/SAF = Northern/Southern Atlas Fault system.
Modified from Michard (1976) and Carte Géologique du Maroc (1985).

low magnitude, with historical earthquakes of <4.9 distributed ~10 km downstream of the study area along the South Atlas Mountain front region (Medina and Cheraoui, 1991). Thus, tectonics has created the drainage network in which the study area tributary fans occur but low levels of historical seismicity suggest that active tectonics play a low-negligible role in fan sediment supply (e.g., via earthquake-related landslides: Hughes et al., 2014), with climate being the principal driver.

A series of regional fold and thrust fault structures dominate the tectonic configuration of the study area (Fig. 2). In upstream study reaches an open and low gradient symmetric anticline and syncline exists. In middle reaches, an asymmetric syncline with a near vertical SE limb and gentler dipping NW limb occurs. In the downstream reach the asymmetric syncline becomes thrust faulted. This structure controls the drainage network configuration, with the River Dades routed down the fold axes and tributary streams developed onto the fold limb dip slopes (Stokes et al., 2008). This structural pattern primarily affects a sequence of Jurassic sedimentary bedrock (Fig. 2), dominated by marine carbonates (limestone and mudstone) with subordinate terrestrial conglomerate, sandstone, and pedogenically altered mudstone (Table 1).

Furthermore, the stratigraphic configuration and bedrock lithology are significant for influencing the sediment supply from the tributary drainage network and the tributary/trunk drainage valley morphologies. Valley morphology varies according to structure and lithology. For example, thrust faulted Jebel Choucht Formation limestone (Pliensbachian marine: Fig. 2; Table 1) in downstream reaches has resulted in a structurally thickened sequence into which vertical fluvial incision has dominated, forming narrow and deeply incised canyons (Stokes et al., 2008) that confine space for tributary-junction fan formation. In contrast, the more open folded areas with normal stratigraphic thicknesses in middle and upstream reaches form wider valleys providing more space for tributary-junction fan sedimentation. This is especially evident from the mudstone-dominated Ouchbis Formation (Pliensbachian marine: Fig. 2) in the middle study reach areas. Similar lithology–morphology relationships are evident for sediment supply and storage, which tends to be greater in weaker bedrock areas (e.g., mudstone). Sediment supply relates bedrock erodibility but also the relationship between bedrock dip and a channel (slope-channel coupling: sensu Harvey, 2002a). In the study area, weak lithologies (e.g., mudstones) or lithologies with a high degree of heterogeneity (e.g., thin interbeds of limestone and mudstone) tend to readily erode. If these litholgies are part of a hillslope that dips directly or obliquely into a channel, then sediment supply can be high and further enhanced by slope undercutting and material translation (e.g., Weissel and Seidl, 1997). In contrast, slopes that dip obliquely or away from the channel supply less sediment. Relationships between lithology and valley morphology have been examined within parts of the study area by Dłużewski et al. (2013) but not in the context of alluvial fan sites.

The detailed study area is 20-km-long and covers an area of ~500 km^2 (Fig. 3A). Within this area the topography reaches a height of 3198 m at the drainage divide in the northwest and a lowest elevation of 1686 m in the southwest in the valley floor of the 'Main Dades Gorge'. The River Dades is perennial (Fig. 4A–C) flowing SW through the study area (Fig. 3A). Discharge measurements are only available from the Ait Moutade gauging station (UTM = 30R 215207 E; 3479564 N), some 20 km downstream of the study area. Here, the average daily discharge is ~33.3 m^3/s with peaks linked to winter-spring precipitation (Schulz et al., 2008; Dłużewski et al., 2013). The rainfall and discharge are characteristic of a semiarid mountain climate but with a marked altitude gradient; with 200 mm annual precipitation upstream at Msmerir (2000 m altitude) reducing to 150 mm downstream at Boulmane du Dades (1526 m) (Schulz et al., 2008; Dłużewski et al., 2013). Lower order streams that form NW–SE orientated tributaries to the River Dades (Fig. 3A) are ephemeral (Fig. 4A–D) and are only activated by rare, often localised storm events (Dłużewski et al., 2013). This contrasts with the River Dades whose perennial flows are linked to annual winter–spring snow/rain precipitation in higher altitude watershed

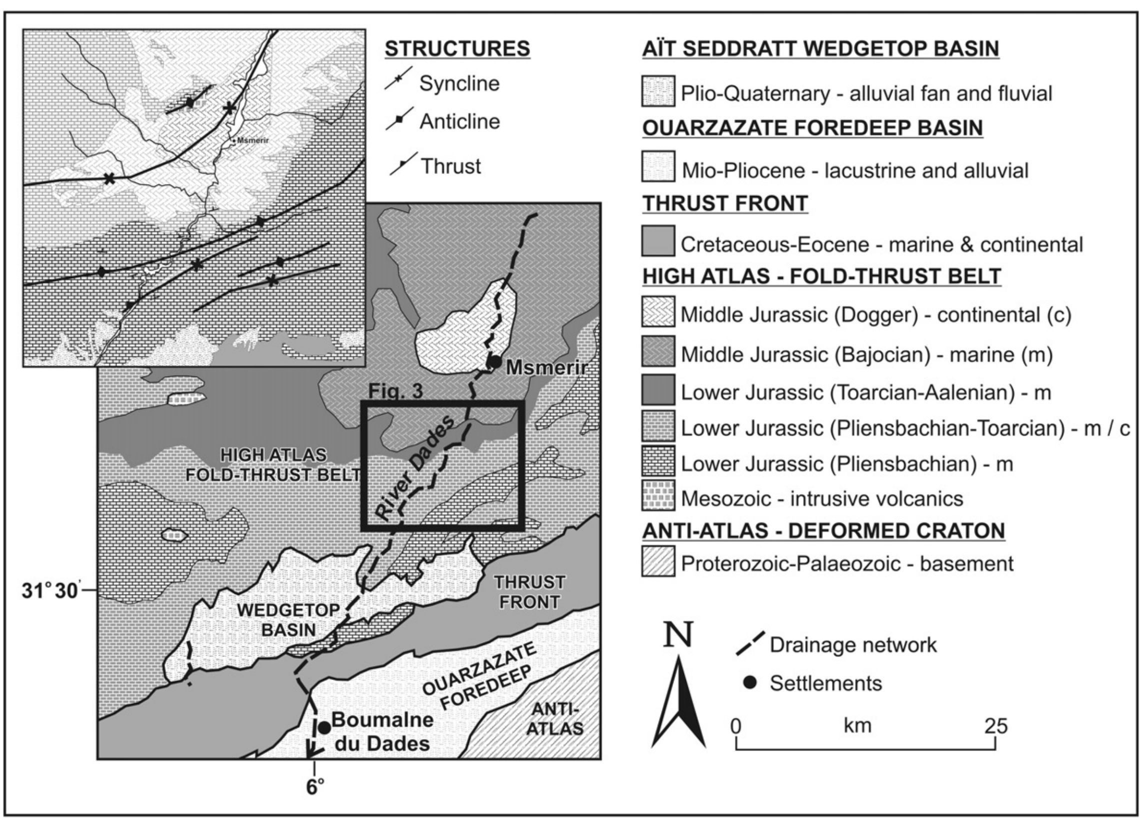


Fig. 2. Simplified regional geology and structure (inset) of the River Dades and its routing through the High Atlas orogenic system components. Modified from Carte Géologique du Maroc (1993).

Table 1
Study area stratigraphic formations and lithologies (Carte Géologique du Maroc, 1990; Carte Géologique du Maroc, 1993).

		Formation name	Lithologies	Study area coverage		Average rock strength
				km^2	%	
Quaternary		Quaternary	Conglomerates, breccias in river terraces and landslide complexes.	30.0	5.9	Weak
Plio-Quaternary		Plio-Quaternary	Continental fluvial and fan conglomerates: cemented carbonate cobbles.	2.3	0.5	Weak
Jurassic	Bathonian	Guettioua	Continental sandstones, red mudstones and channelized conglomerates.	8.3	1.7	Weak
	Bajocian–Bathonian	Tillougguit	Marginal marine and continental sandstones, siltstones and micro-conglomerates.	7.4	1.5	Weak
	Bajocian	Bin El Ouidane	Marginal marine platform oolitic limestone and marls.	117.3	23.3	Strong
	Aalenian	Azilal	Continental and marginal marine silts, marls, sandstones and dolomites.	36.8	7.3	Weak
	Toarcian	Tafraout	Continental fluvial and marginal marine/coastal plain marls, silts and sandstones.	126.0	25.0	Intermediate
	Toarcian	Tagoudit	Deep marine rhythmic marls, silts and sandstones.	4.7	0.9	Weak
	Sinemurian–Pliensbachian	Jbel Choucht	Massive marine platform limestone with algae and large bivalves.	48.8	9.7	Strong
	Sinemurian–Pliensbachian	Ouchbis	Interbedded deep marine rhythmic limestone and marl.	34.5	6.8	Intermediate
	Sinemurian–Pliensbachian	Aberdouz	Interbedded marine dark grey/black limestone and marl.	86.6	17.2	Weak
	Hettangian–Sinemurian	Agoulzi	Laminated marine limestone and dolomite.	0.5	0.1	Weak
Late Triassic		Volcanics	Basalt.	0.7	0.1	Weak
			Total area	504		

regions (Schulz and de Jong, 2004) and rarer convective storm events that affect the desert region of NW Africa (Fink and Knippertz, 2003; Knippertz et al., 2003). Tributary channel floors comprise mixed bedrock and gravel alluvial reaches (Fig. 4A, B, D). Knickpoints are common along the tributary streams and can be several metres high, normally associated with strong and thick limestone units (Fig. 4D). Tributaries usually display highly stepped channel morphology, especially in bedrock reaches, reflecting variations of lithological strength within some of the geological formations in the study area (e.g., Tafraout and Bin El Ouidane Formations). Some tributary catchments are dominated by alluvial reaches, including occurrences of tributary junction alluvial fans (Figs. 3B and 4A–C). Other tributary channel catchments are dominantly bedrock, suggesting limited sediment supply or that sediment generated is efficiently transported into the trunk drainage. Catchment slopes lack vegetation cover, comprising bare rock and patches of thin (dm-scale) soil and/or slope colluvium that collectively enhances opportunities for high sediment yields from tributary catchments. Where present, catchment vegetation is of a steppe type at lower altitudes with rare trees above ca. 2400 m (de Jong et al., 2008).

Much of the River Dades valley floor is characterised by a gravel floodplain/terrace that has been locally reworked for agriculture (Fig. 4B). The river can be incised by several metres into this valley floor. Where they occur, the tributary-junction alluvial fans build out over and onto the floodplain/terrace surface. The floodplain/terrace can be occupied during flood events and the sediments can be reworked. The fans are modern to Holocene features, postdating inset Quaternary river terraces and rare, exceptionally large tributary fan features (Fig. 4E).

3. Methods

3.1. Remote sensing and field survey

Research was conducted using an integrated remote sensing and field approach that specifically targeted the distal part of the fold-thrust belt region of the mountain belt. Here, tributary-junction fans are relatively common features; and there is consistency in morphological setting, bedrock geology, structure, and uplift history that are typical of similar orogenic zones in the broader High Atlas region and similar collisional mountain belts worldwide. The remote sensing utilised satellite imagery (Landsat, SPOT), digital elevation model datasets (30 m/90 m SRTM), 1:40,000 black and white vertical aerial photos (ANCFCC, 1997), topographic maps (Carte du Maroc, 1968a,b), and geological maps (Carte Géologique du Maroc, 1990, 1993) using the Arc GIS (10.1) and Google Earth (Pro) platforms. These data sets were used to map the drainage networks, catchment areas and tributary-junction settings. Field walkover surveys were conducted to verify remote sensing analyses. This involved targeted mapping and surface profiling of fan and nonfan catchments and tributary junction settings using a Trupulse laser range finder and a Trimble Geo-XH GPS.

3.2. Rock strength

Bedrock geology is significant for (i) drainage network/catchment configuration, (ii) sediment supply to the trunk drainage (e.g., Stokes et al., 2008; Dłużewski et al., 2013), and (iii) control on trunk valley morphology. Within the study area, the bedrock geology is represented by 13 different stratigraphic units (Table 1; Fig. 5A) comprising a range of different sedimentary lithologies (limestone, mudstone, siltstone, sandstone, and conglomerate). These lithologies possess different strength properties based upon combinations of lithology textures (granular vs crystalline), cementation and discontinuity (joints, fractures, bedding, etc.) parameters.

Two strength types were identified based upon (i) qualitative strength properties (above) and (ii) quantitative in situ mass strength measurements using a Schmidt hammer (Goudie, 2006) (measurements from multiple locations comprising 32 impact readings, removal of highest and lowest 'outliers', and expression of an average rebound value):

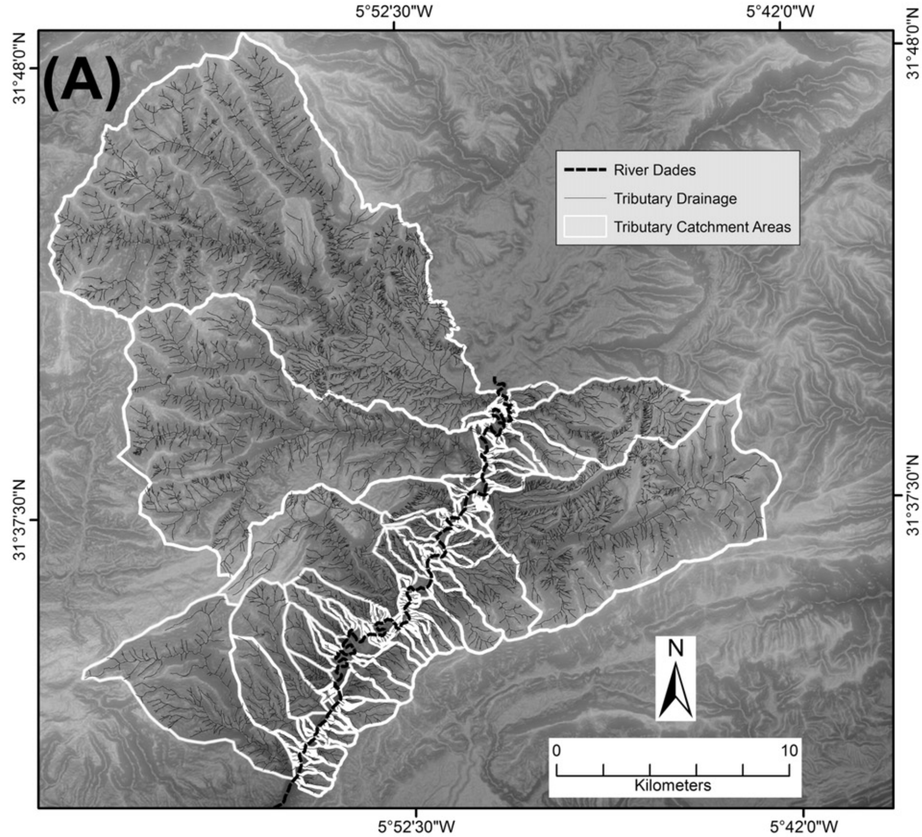
Type 1 — massive crystalline limestone or cemented conglomerates or sandstones with Schmidt hammer values of 40 to 60. Rock surfaces display minimal discolouration. Rock weathers/erodes into decimetre blocks or slabs.

Type 2 — poorly cemented sandstone, siltstone, and mudstone with Schmidt hammer values of $<$30. Rock surfaces are discoloured, and rock mass possesses a well-developed fissile fabric conducive to granular weathering characterised by marked disintegration.

The study area geology was remapped using GIS according to strength type (Fig. 5B). This in turn enabled a catchment rock strength classification to be determined (Fig. 5C). Catchments that comprised $>$70% of type 1 were considered to have a 'strong' rock strength, 50 to 70% type 1 as 'intermediate' strength, and $<$50% type 1 as 'weak' strength. Comparison of catchments that generated fans and those that did not enabled the role of rock strength for tributary fan formation to be explored.

3.3. Catchment, trunk valley drainage and tributary fan variables

For each tributary fan and its surrounding area a range of morphological and geological components were described in relation to the (i) catchment, (ii) trunk valley drainage, and (iii) tributary fan variables.



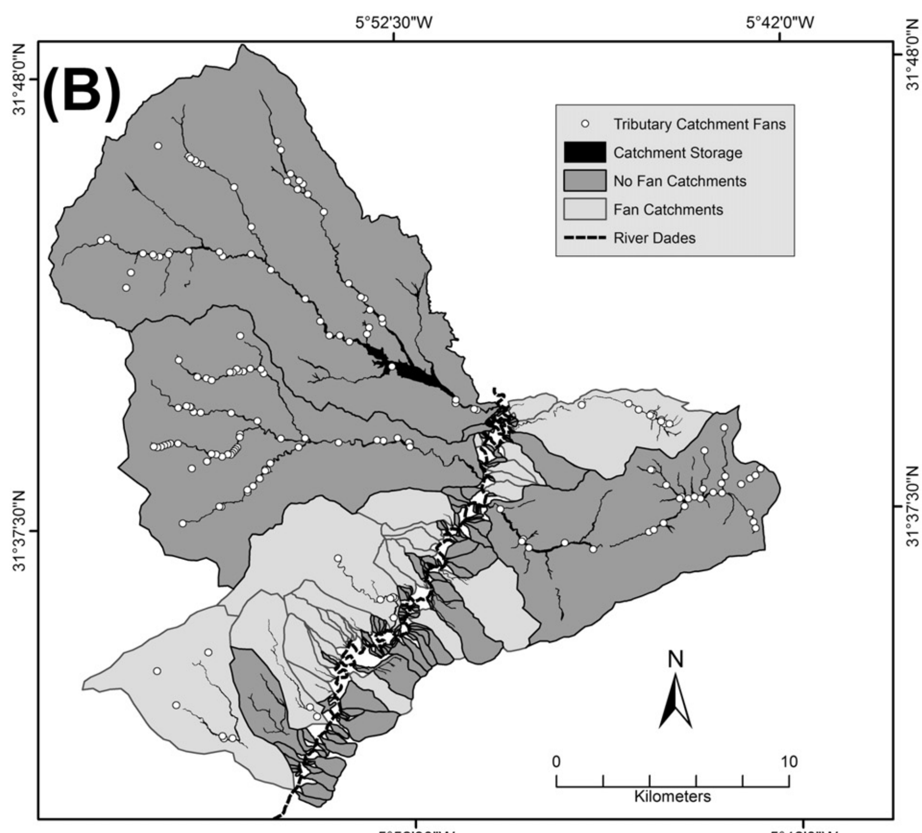


Fig. 3. (A) Detailed study area showing 20-km-long River Dades trunk drainage, tributary stream catchments and their drainage network overlain onto an SRTM 1 arc second derived digital elevation model with hillshade modification (USGS, 2015). (B) Study area tributary catchment sediment storage and alluvial fans (see Fig. 6 for trunk drainage tributary fan occurrence).

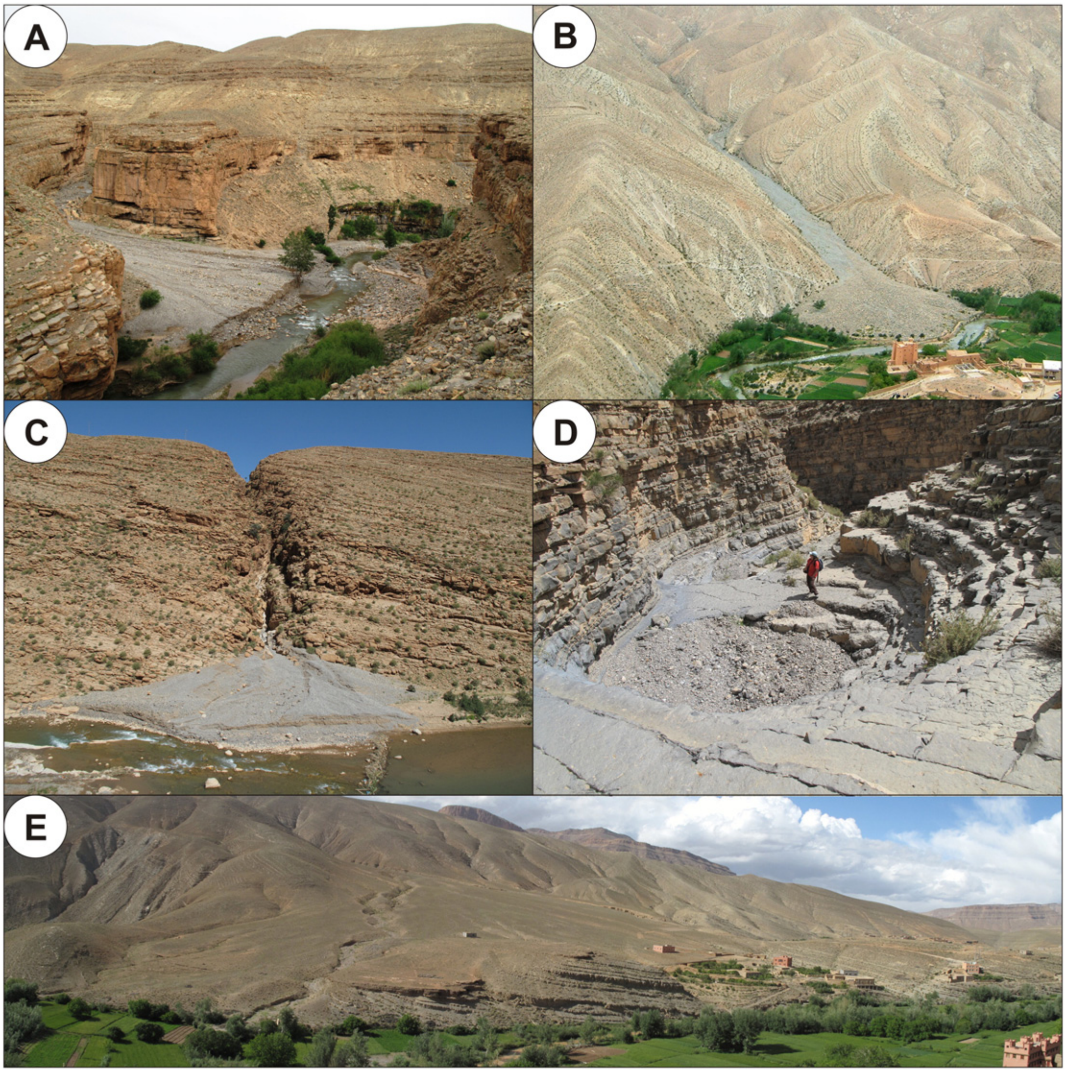


Fig. 4. Study area tributary fan and Dades River valley field imagery. (A) Dades River and tributary fan 28 in the proximal study region. Note the confined canyon morphology and perennial river flow. Fan 28 is ephemeral and has previously blocked the valley. (B) Tributary fan 4 building out onto wide Dades River agriculturally developed floodplain. Note fan backfilling and extensive alluviated tributary channel floor sediment storage. (C) Tributary fan 2 illustrating slot canyon tributary feeder. Dades river flow to left. (D) Ephemeral bedrock tributary channel in fan 4 catchment (~1 km upstream from Dades River), illustrating a large knickpoint and stepped channel morphology. (E) Large relict tributary fan formed during a glacial cold stage period (west valley side, mid study region).

(i) Catchment variables included area, length, relief, sediment storage, and rock strength. The area, length, and relief characteristics were manually mapped and quantified using satellite imagery in GIS and Google Earth Pro followed by targeted field survey verification. The areas of fan catchments vs nonfan catchments were compared in order to see if a size threshold for generating a fan. The rock strength component (Section 3.2) was utilised in order to explore whether fan vs. nonfan-generating catchments were characterised by specific rock strength characteristics. The valley floors of the tributary catchment drainage network were mapped according to bare rock or alluvial sediment coverage. This was to investigate controls on sediment yield (hillside supply, storage, and throughput) for generating fans and their morphological characteristics.

(ii) Trunk valley drainage variables included the presence/absence of tributary fans in the trunk valley, valley width, morphology, bedrock geology, and strata dip. Valley morphology and width were quantified to explore the space available for fan sedimentation. The bedrock geology underlying a given reach where a tributary-junction fan occurs was also considered in order to examine whether the bedrock geology controlled trunk valley morphology and therefore space for tributary-junction sedimentation, a passive control on fan development and shape. Valley morphology is illustrated using type sections representative of the typical valley morphologies encountered throughout the study area. The bedrock geology of the trunk drainage valley was assessed by field measurement of the dip/dip direction of the strata and its local relationship to fan position and shape. The fan-bedrock dip/direction relationships were classified as (i) syn-dip fans (bedrock dips with fan surface), (ii) anti-dip fans (bedrock dips 90° against fan surface), and (iii) oblique dip fans (bedrock dips at an oblique angle to the fan surface). The fan shape categorisation involved a classification into (i) trimmed, where a proportion of the fan body has been removed by erosion from the trunk drainage, and (ii) lobate, demonstrating unconfined fan sedimentation onto the valley floor. These shape classifications demonstrated the ability of the trunk drainage valley morphology, width, and flood regime to promote or inhibit fan formation or to modify a fan once created.

(iii) Tributary-junction fan variables included fan location, spacing, shape, area, gradients, and process. Fan shape and areas were mapped using satellite imagery with verification from a field walk-over survey to verify accuracy. Fan gradient and process were

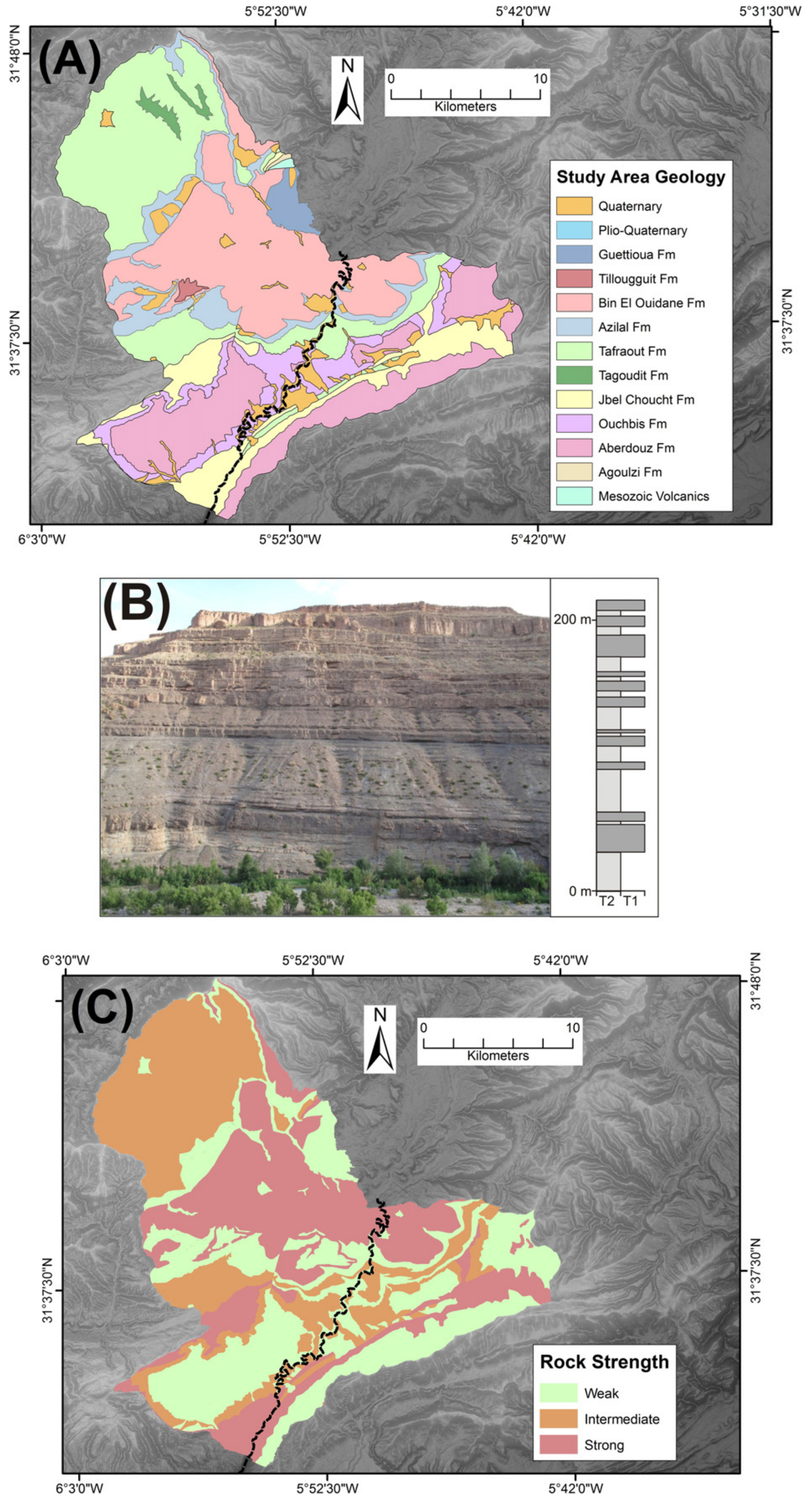


Fig. 5. (A) Study area stratigraphy (see Table 1 for details); (B) Section through the Tafraout Formation (30 R 230574 E 3502818.60 N) and an example of rock strength classification (T1/T2 = type 1 or 2: see Methods for explanation); (C) Remapping of catchment rock strength classification.

assessed from the field survey where fan surface morphology (planar vs. undulating) and sections through fan sediments were used to classify fan formation from debris flow or fluvial processes. Debris flows were characterised by poor sorting, matrix support of larger clasts, a lack of sediment fabric/organisation, and an undulating/lobate fan surface morphology. Fluvial processes were characterised by better sorting, clast supported and imbricated fabrics, stratification, and a relatively smooth/flat fan surface morphology. Classification of fan processes allowed for more detailed exploration of the process-form relationships that commonly exist for alluvial fans, including those at tributary junction settings (e.g., Harvey, 1997; Al-Farraj and Harvey, 2005).

3.4. Morphometric analyses

The morphological characteristics of the tributary-junction fans were explored further using qualitative and quantitative analyses. The qualitative analyses involved examining the graph plots of (i) valley width and fan shape, (ii) the dip of bedrock geology strata and fan process, (iii) fan area and process, (iv) fan gradient and process, (v) catchment area and fan process, and (vi) catchment gradient and relief. The quantitative analyses followed standard alluvial fan morphometric approaches (e.g., Harvey, 2002b) and involved regression that explored the significance of relationships between the respective dependent and independent variables of (i) fan and catchment area, (ii) fan gradient and catchment area, (iii) catchment length, gradient, and relief, (iv) fan area and fan gradient, and (v) catchment/fan area ratio and valley width. The residuals (deviations from the predicted best fit line) of the catchment area vs. the fan area and the catchment area vs. fan gradient regressions (Harvey, 2002b) were then calculated and plotted graphically in order to explore further whether fans displayed certain gradient and area characteristics that could be related to the catchment (e.g., sediment yield) and/or trunk valley components (e.g., confinement).

4. Results

4.1. Catchments

The 504-km^2 study area comprised 186 tributary catchments that drained into the River Dades trunk valley (Fig. 3). Summary of the morphological characteristics of these catchments are presented in Table 2 and Fig. 6. The tributary catchments ranged from 161 to 0.003 km^2, with catchment areas of <1 km^2 being the dominant size (86%) (Fig. 6A). Relief of these catchments varied from 1515 to 41 m (Fig. 6B), whilst catchment length ranged from ~18.9 km to ~110 m (Fig. 6C). Combined, these produced catchment gradients that varied from 0.08 to 0.96, with catchments of <0.5 dominating (74%) (Fig. 6D). Tributary catchment drainage is routed SE or NW into the River Dades trunk drainage (Fig. 3A) configured to the regional fold structures (Fig. 2; Stokes et al., 2008). Tributary catchments appear to be equably positioned onto both limbs of the regional fold structures (NW = 51% vs. SE = 49%). Catchment geology is dominated by three stratigraphic units comprising the Tafraout (25%), Bin El Ouidane (~23%), and Aberdouz Formations (~17%) (Fig. 5A) characterised by interbedded successions of carbonate (limestone-mudstone) and/or siliciclastic (sandstone–mudstone) lithologies (Table 1). Tributary valley floors are dominantly bedrock (Figs. 3 and 4D) but alluviated reaches are present, but confined to only 20 catchments (Fig. 3B). These alluviated tributary catchments have larger areas ranging from 1.5 to 161 km^2. For a given catchment, the alluviated reaches have limited spatial occurrence comprising <3% of the catchment area.

Of the 186 catchments, only 29 (16%) generated alluvial fans at the tributary junction with the River Dades (Fig. 7). The characteristics of the fan-generating catchments are presented in Tables 2 and 3. Fan generating catchments cover a total area of ~120 km^2, some 24% of the study area (Fig. 3A). When all catchments are considered (Fig. 6B), reliefs of >578 m appear to be more likely to produce fans; and these fan-generating catchments appear to be characterised by higher relief, longer lengths, and lower gradients than nonfan-generating catchments (Table 2; Fig. 6). Fan-generating catchments are more typically associated with the NW fold limb regions, draining SE into the River Dades (Figs. 2 and 7). These drainages are configured to the dip of the bedrock enhancing the possibility for elevated sediment supply and more effective slope-channel coupling. When all catchments are plotted in size area order three observations can be made (Fig. 6A): (i) catchment areas of <0.12 km^2 do not generate alluvial fans, (ii) catchments between 0.12 and 0.878 km^2 start to generate alluvial fans but ‘no-fan’ generation still dominates (75%), and (iii) catchments >0.88 km^2 are characterised by a notable increase and dominance of alluvial fan generation (68%). The geology of the fan-generating catchments is characterised primarily by limestone-mudstone lithologies dominated by the Aberdouz Formation (34%), with lesser (but still notable) contributions from the Ouchbis (18%), Jebel Choucht (16%), and Bin El Ouidane (12%) Formations (Fig. 5A). When considered in catchment rock strength terms (Table 3; Fig. 5C), the no-fan-generating catchments are characterised by equable distributions of rock strength (weak = 33%; intermediate = 33%; strong = 34). In contrast, the fan generating catchments are dominated by weak rock strengths (weak = 47%; intermediate = 25%; strong = 28%). This suggests catchments with higher proportions of weak bedrock in their catchments are more likely to generate tributary-junction alluvial fans.

The fan-generating catchments have more common occurrences of alluviated reaches, with ~48% of the fan-generating catchments showing evidence for sediment storage (Table 2; Figs. 3B and 7). Some of the largest tributary-junction fan catchments (areas = 8 to 29 km^2) have alluvial fans within their catchments suggesting high rates of sediment supply and storage. However, the largest of all tributary catchments are ones that do not generate tributary-junction alluvial fans. These catchments have the highest coverages of alluviated reaches (2.3 to 2.7% of a given catchment area) and contain the largest numbers of within-catchment tributary fans (32 to 62). This suggests that once catchment areas get to a certain size (here >29 km^2) they have a greater potential to store sediment, suppressing tributary junction fan formation despite the potential for generating larger flood discharges.

4.2. Trunk valley

The trunk valley is occupied by the River Dades and its floodplain whose valley has a general NE–SW orientation occupying the axis of

Table 2
Tributary catchment morphological characteristics for (i) all catchments, (ii) no-fan-generating catchments, and (iii) fan-generating catchments.

	Area (km)			Relief (m)			Length (m)			Gradient		
	All	No fans	Fans	All	No fans	Fans	All	No fans	Fans	All	No fans	Fans
Mean	2.56	2.28	4.09	384	305	813	1369	1024	3241	0.39	0.41	0.29
Max	161	161	29	1515	1515	1343	18,907	18,907	9968	0.96	0.96	0.56
Min	0.003	0.003	0.11	41	41	302	109	109	716	0.08	0.08	0.10
Standard deviation	14.57	16	7.19	351	300	294	2302	2161	2167	0.18	0.18	0.09

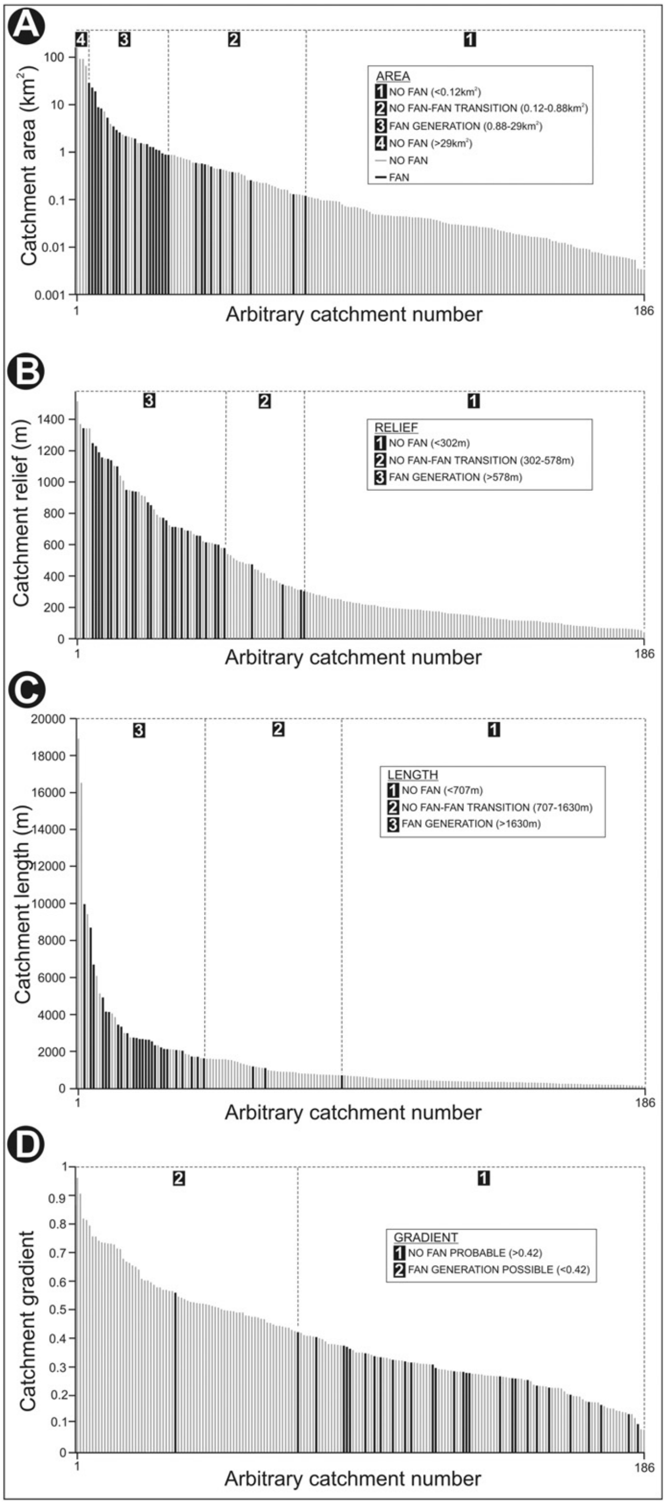


Fig. 6. Fan vs. no fan tributary catchment area (A), relief (B), length (C), and gradient (D) characteristics.

one of the regional synclines (Fig. 2; Stokes et al., 2008). The trunk valley comprises relatively straight and highly sinuous reaches (Fig. 3A) that appear to be related to combinations of rock strength, stratigraphic arrangement and structural configuration of the bedrock sequence. Straighter reaches are associated with tectonically thickened strong limestone-dominated bedrock canyons (Stokes et al., 2008), whilst higher sinuosity reaches are associated with interbedded limestone–mudstone and sandstone–mudstone arrangements that are gently dipping. The width of the trunk valley floodplain is important for providing the space for fan construction. Basal valley widths vary between 9 and 265 m (mean = 112 m) (Fig. 8A). Narrower valleys (i.e., those <112 m) are typically associated with limestone of the Jebel Choucht Formation (mean width = 65 m), forming box-like or *v*-shaped canyon morphologies (Fig. 8A, B). Wider valleys (>112 m) are associated with the interbedded limestone-mudstone units of the Ouchbis Formation (mean width = 161 m) forming more open shaped morphologies (Fig. 8A, C). The fan and no-fan tributary-junction sites appear distributed across the full range of valley width values (Fig. 8A). However, this simple approach does not reveal any obvious relationships between fan size and valley width, despite the commonly stated importance of valley confinement in tributary-junction fan research (e.g., Al-Farraj and Harvey, 2005; Gómez-Villar et al., 2006; Wang et al., 2008). This relationship is explored further in Sections 4.3 and 5.4.

4.3. Tributary-junction fans

The 29 tributary-junction fans have a spacing distribution of between 0.2 and 3.5 km (mean = 1.2 km) along the length of the River Dades (~32.5 km) (Fig. 7). There is some geological explanation since some 59% ($n = 17$) of the fans are distributed at <0.9-km intervals along the trunk valley dominated by the limestone-mudstone interbeds of the Ouchbis Formation. This contrasts with the limited fan occurrence where the trunk valley is made of Jebel Choucht Formation limestone (10%/$n = 3$), where the fans are distributed at ~2-km intervals. Thus, stronger bedrock suppresses drainage network development and therefore impacts upon the potential for tributary-junction fan development, whilst weaker bedrock enhances it.

Tributary-junction fan mapping allowed two shape classifications to be determined: (i) trimmed and (ii) lobate (Fig. 9). These classifications were based upon whether the fan was longitudinally and/or laterally confined by the trunk valley into which it was building and its proximity relationship to the River Dades active channel. Trimmed fans were least common (17%; Table 3) and tended to be associated with areas dominated by limestone (e.g., Jebel Choucht and Bin El Ouidane Formations). These limestones form canyon-like valley reaches with variable but typically narrow valley widths (average = ~79 m) and often high and steep, sometimes vertical canyon walls (e.g., Fig. 4A). Such configurations lead to a more dynamic interaction between the tributary fan and River Dades, resulting in confined fan development and fan toe erosion. Lobate fans were the most common fan shape (83%). Fan construction is both laterally and longitudinally unconfined into wider valley reaches dominated by the limestone-mudstone interbeds of the Ouchbis Formation (average = ~159 m) and with little influence from the River Dades active channel (e.g., Fig. 4B). However, despite these lithological controls on valley shape and width and how these in turn influence fan shape, the role of valley confinement for fan building remains unclear. This is explored further in Section 5.4.

Field mapping and surveying of the tributary fans enabled fan area and surface gradient quantification (Table 3; Fig. 10). Tributary fan areas varied from 0.007 to 0.026 km^2, with a mean area of 0.0053 km^2. Fans with areas of 0.001 to 0.005 km^2 were the most common (~50%) suggesting a dominance of small-to intermediate-sized fans. Fan surface gradients ranged from 0.05 to 0.3, with a mean gradient of 0.115. The gradients could be grouped into low gradient (<0.1) or steep (>0.1) with a dominance of lower gradient forms (58%).

The sedimentary processes that constructed the tributary-junction fans are debris flow and fluvial processes (Fig. 11; Table 3). Fans constructed from debris flows were dominant (73%), although some of these fans showed mixing with subordinate fluvial processes. Comparison of fan process with fan area and gradient revealed some relationships (Fig. 10). A weak visual relationship was evident for fan area and process, with larger fan areas more commonly being characterised by fluvial processes and smaller fan areas by debris flows. A stronger visual

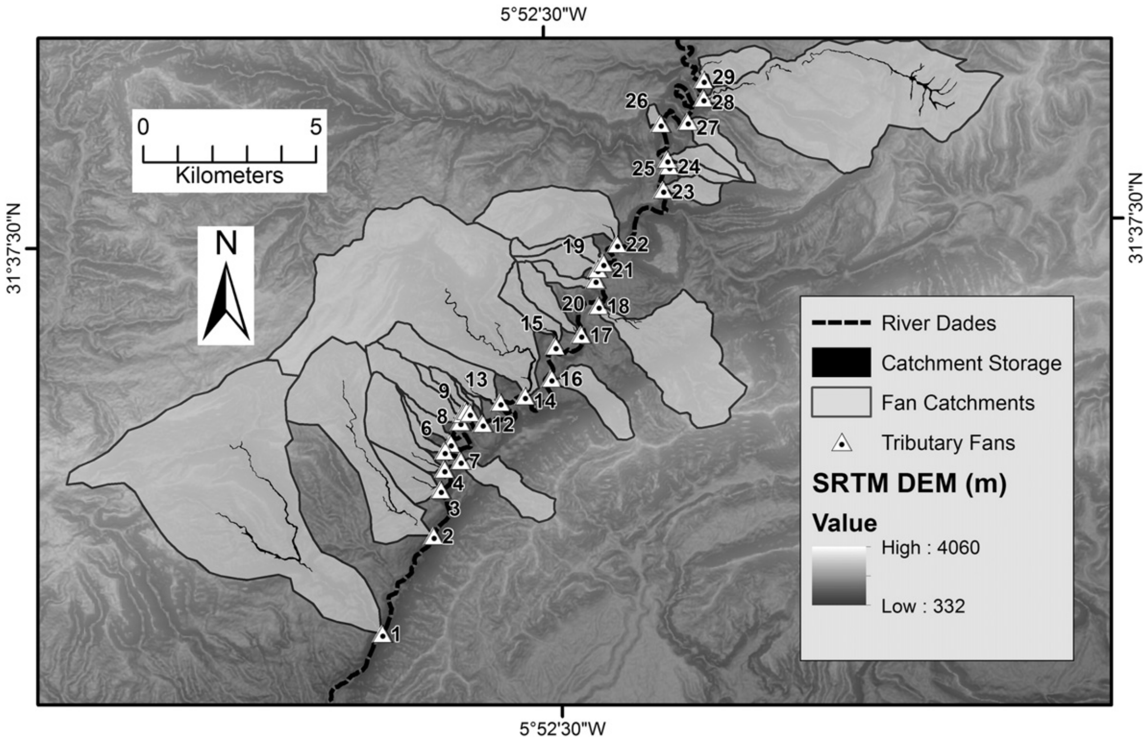


Fig. 7. Tributary fan-generating catchments.

Table 3
Morphological, sedimentary process, geological, sediment storage and rock strength characteristics of tributary junction fans and their respective valley and catchment settings.

Fan no.	Location (UTM Fan)	Tributary fans					Valley		Catchment										
		FA (km^2)	FG	FP	FS	FGD	VW (m)	VM	CA (km^2)	CR (km)	CL (km)	CG	CP	Storage			Rock strength (%CA)		
														km^2	%	NF	W	I	S
1	30R 221799.03 E 3491160.78 N	0.006	0.0138	F	T	SD	46	c	28.9	1.343	9.968	0.13	NW	0.29	1	6	58	20	22
2	30R 223439.80 E 3493912.43 N	0.002	0.0251	F	L	SD	61	c	8.79	1.233	6.081	0.20	NW	0.14	1.6	2	55	24	21
3	30R 223719.00 E 3495237.67 N	0.005	0.0133	F	L	SD	142	o	1.47	0.615	2.625	0.23	NW	0.02	1.4	0	43	48	9
4	30R 223855.80 E 3495825.88 N	0.013	0.0113	DF	L	SD	182	o	2.925	0.949	3.336	0.28	NW	0.02	0.7	0	93	7	0
5	30R 224084.79 E 3496565.84 N	0.003	0.0337	DF	L	SD	74	o	0.555	0.755	2.332	0.32	NW	0.002	0.1	0	99	1	0
6	30R 223892.61 E 3496355.82 N	0.002	0.0130	DF	T	OSD	105	o	0.495	0.771	2.121	0.36	NW	0	0	0	84	16	0
7	30R 224341.35 E 3496050.69 N	0.004	0.0066	DF	L	SD	142	o	2.01	0.941	2.982	0.32	SE	0	0	0	64	9	27
8	30R 224398.74 E 3497177.48 N	0.006	0.0211	DF	T	OSD	92	o	2.18	1.148	3.439	0.33	NW	0.01	0.3	0	82	16	1
9	30R 224467.64 E 3497407.37 N	0.002	0.0427	DF	L	OSD	134	o	0.38	1.139	2.036	0.56	NW	0	0	0	100	0	0
10	30R 224578.66 E 3497484.33 N	0.002	0.0350	DF	L	SD	101	o	0.44	0.603	1.630	0.37	NW	0	0	0	100	0	0
11	30R 224678.68 E 3497422.52 N	0.001	0.0617	DF	L	OSD	104	o	0.13	0.443	1.184	0.37	NW	0	0	0	100	0	0
12	30R 225040.36 E 3497088.88 N	0.001	0.0530	DF	L	SD	175	o	0.12	0.311	1.102	0.28	NW	0	0	0	100	0	0
13	30R 225579.95 E 3497682.86 N	0.026	0.0079	DF	T	OSD	223	o	2.595	1.157	4.148	0.28	NW	0.03	1.3	0	87	12	1
14	30R 226299.89 E 3497824.71 N	0.005	0.0170	F	L	OAD	165	o	23	1.189	6.696	0.18	NW	0.24	1	6	30	32	37
15	30R 227268.00 E 3499216.30 N	0.013	0.0204	DF	L	OAD	209	o	1.28	0.713	2.672	0.27	NW	0.03	1.7	0	13	87	0
16	30R 227095.86 E 3498288.95 N	0.002	0.0237	F	L	OSD	156	o	1.92	1.100	2.721	0.40	SE	0.03	0.5	0	84	0	16
17	30R 228031.50 E 3499512.85 N	0.014	0.0070	F	E	OSD	154	o	1.29	0.713	2.747	0.26	NW	0.01	0.5	0	16	84	0
18	30R 228575.34 E 3500322.26 N	0.002	0.0349	DF	L	SD	133	o	8.285	1.248	4.912	0.25	SE	0.04	0.5	0	58	33	9
19	30R 228602.43 E 3501387.23 N	0.001	0.0185	DF	L	AD	164	o	0.57	0.600	1.726	0.35	NW	0	0	0	28	72	0
20	30R 228531.07 E 3501077.70 N	0.001	0.0308	DF	E	SD	243	o	1.09	0.707	2.539	0.28	NW	0	0	0	9	91	0
21	30R 228782.39 E 3501549.89 N	0.007	0.0123	DF	L	OAD	154	o	0.885	0.852	2.667	0.32	NW	0	0	0	58	42	0
22	30R 229210.64 E 3502079.33 N	0.015	0.0108	DF	L	AD	126	c	5.28	0.939	4.127	0.23	NW	0.02	0.4	0	37	19	44
23	30R 230631.03 E 3503579.59 N	0.004	0.0111	DF	L	SD	84	c	0.94	0.578	1.713	0.34	SE	0	0	0	62	29	10
24	30R 230842.59 E 3504259.68 N	0.002	0.0183	DF	E	OSD	147	c	0.595	0.658	2.134	0.31	SE	0	0	0	30	0	70
25	30R 230799.53 E 3504451.01 N	0.002	0.0254	DF	L	OSD	115	c	0.88	0.657	2.219	0.30	SE	0	0	0	11	0	89
26	30R 230662.49 E 3505495.83 N	0.001	0.0476	DF	L	OAD	103	c	0.255	0.302	0.716	0.42	NW	0	0	0	6	0	94
27	30R 231449.41 E 3505520.99 N	0.003	0.0162	DF	E	SD	68	c	1.13	0.689	2.643	0.26	SE	0	0	0	14	0	86
28	30R 231939.90 E 3506162.44 N	0.008	0.0146	F	T	OAD	52	c	19.03	0.870	8.692	0.10	SE	0.34	1.8	0	27	29	44
29	30R 231979.69 E 3506701.14 N	0.002	0.0141	F	E	OSD	116	c	1.54	0.346	2.073	0.17	SE	0.02	1.1	0	10	0	90

Tributary Fans: F = fan; FA = fan area; FG = fan gradient; FP = fan process (F = fluvial; DF = debris flow); FS = fan shape (T = trimmed; L = lobate); FGD = fan geology dip (SD = syn-dip; AD = anti-dip; OSD = oblique syn-dip; OAD = oblique anti-dip).
Valley: VW = valley width; VM = valley morphology (o = open, c = canyon).
Catchments: C = catchment; CA = catchment area; CR = catchment relief; CL = catchment length; CG = catchment gradient; CP = catchment positioning (with respect to NE–SW routed trunk drainage); Storage: NF = number of fans; Rock Strength: W = weak, I = intermediate, S = strong.

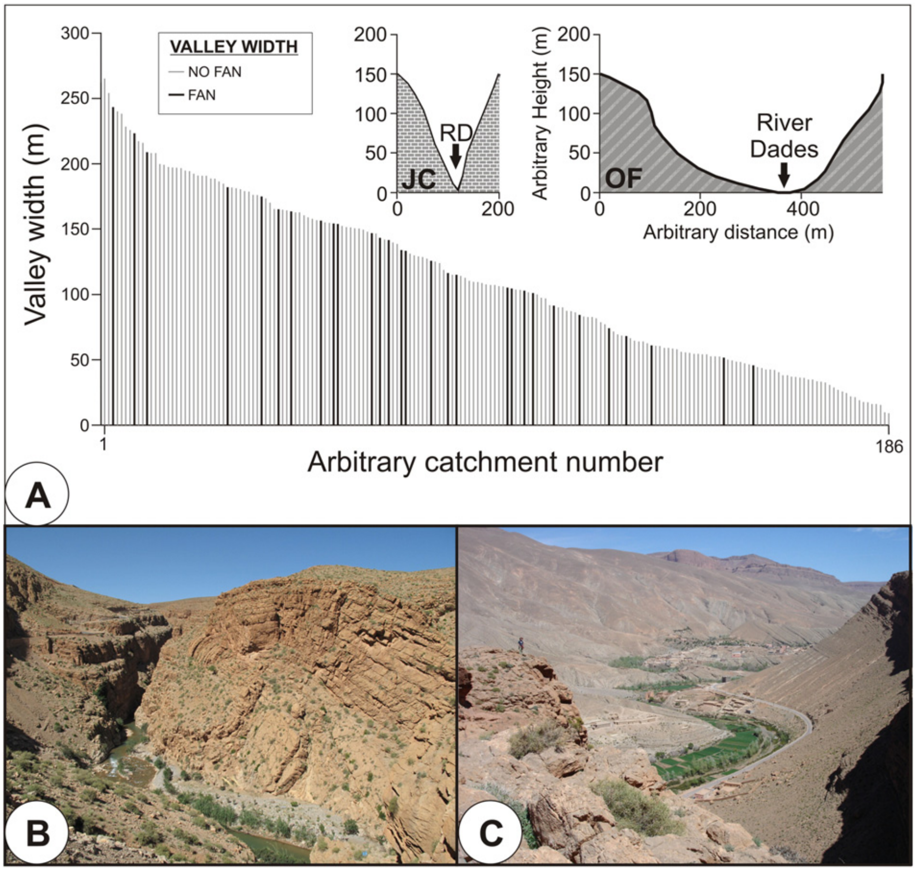


Fig. 8. Valley width characteristics of the River Dades trunk valley. (A) Plot of trunk valley widths adjacent to the no-fan- and fan-generating tributary catchments. Inset illustrates typical valley cross profiles for open and confined valley settings (JC = Jebel Choucht Fm; OF = Ouchbis Fm;). (B) Field imagery of a typical narrow/confined valley form underlain by folded and thrust-faulted JC geology. (C) Field imagery of a typical open valley form underlain by OF geology.

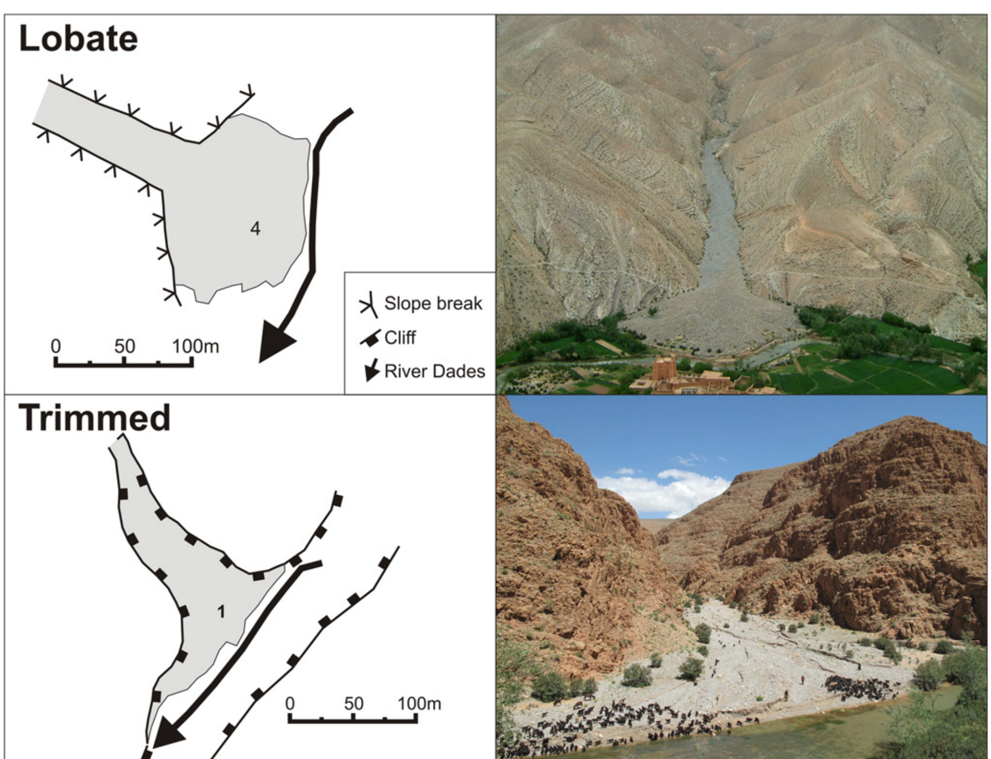


Fig. 9. Tributary fan shape classifications. See Table 3 for data set classification assignment.

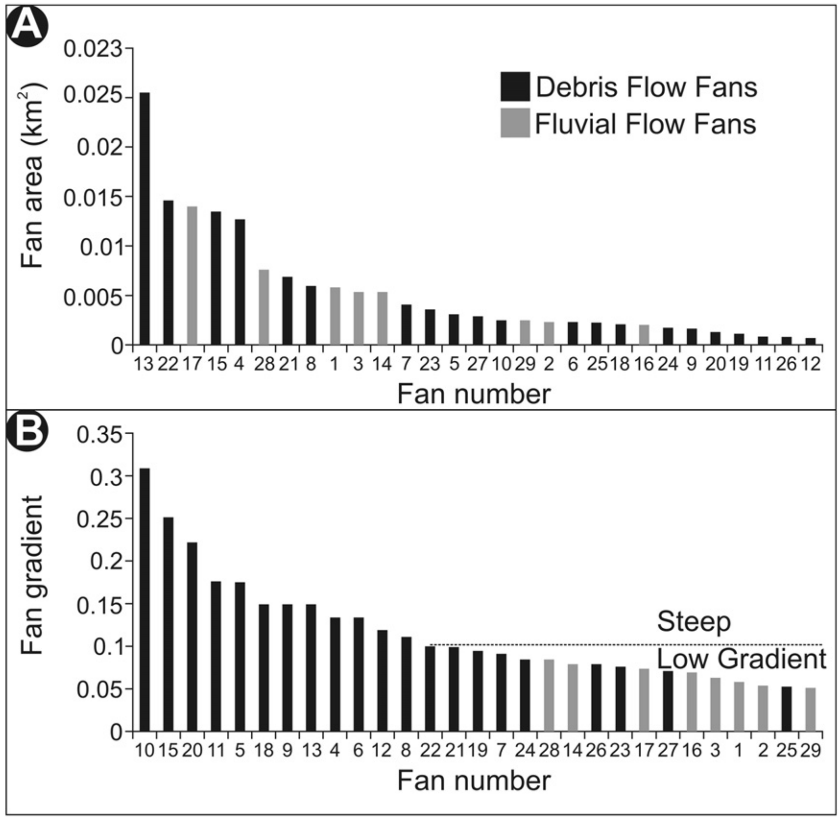


Fig. 10. Tributary fan area (A) and gradient (B) characteristics with sedimentary process classification.

relationship exists between fan gradient and process, where steeper fans are dominated by debris flow processes.

The relationship between fan gradient and process is further enhanced by considering the passive configuration of the bedrock. Syn-dip geology should enhance sediment supply producing more debris-flow-dominated processes. Syn-dip debris flow fans were the dominant process-dip configuration (Fig. 12). However, for fluvial fans alone, the process-dip configurations showed a more equable distribution but with a dominance of syn- and oblique syn-dip types. This difference might be explained by bedrock dip and strength combinations.

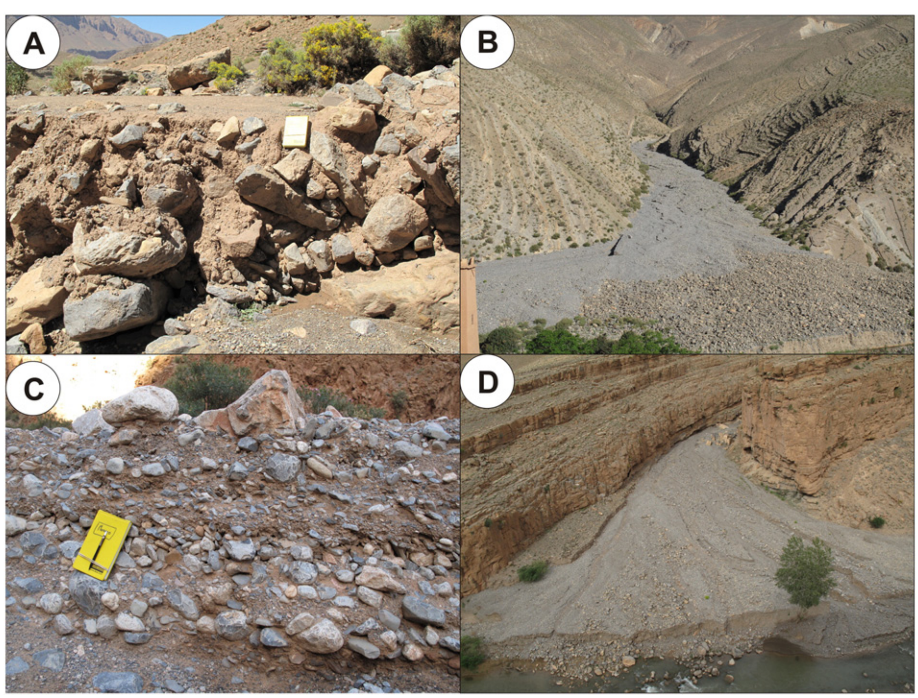


Fig. 11. Tributary fan sediment-process relationships. (A) debris flow deposits (fan 22); (B) debris flow surface morphology (fan 4); (C) fluvial deposits (fan 1); (D) fluvial process surface morphology on fan 28.

When the rock strength of tributary-junction fan catchments in relation to process is considered (Fig. 5C; Table 3), debris-flow fans are dominated by weak rock strengths (average percent catchment strength: weak = 59, intermediate = 21, strong = 21), whilst fluvial fans show a more equable strength distribution (average percent catchment strength: weak = 40, intermediate = 30, strong = 30). This suggests that catchments with proportionally weaker rock are more likely to generate fans built by debris-flow processes. When process is considered alongside rock strength and bedrock dip, debris-flow fans are dominated by weak rock syn-dip relationships, whilst fluvial fans are typically characterised by stronger rock strength and more mixed dip relationships. This suggests that fan processes are controlled by combinations of rock strength and dip.

5. Morphometric analyses

5.1. Catchment area vs. fan area and gradient analyses

Morphometric analyses enabled a quantitative examination of the tributary-junction fan morphological relationships. Standard approaches involve regression of the fan area (F) and gradient (G) with respect to catchment area (A) using the following equations:

$$F = pA^{q} \quad (1)$$

$$G = aA^{b} \quad (2)$$

The visual appearance of the regression (Fig. 13A, B) suggests (i) a positive relationship between fan and catchment area, where bigger catchments tend to produce larger fans (Fig. 13A); and (ii) an inverse relationship between catchment area and gradient exists, where smaller catchments produce steeper fans (Fig. 13B). However, the correlation coefficient values are low (Table 4) suggesting weak but significant (>95%) statistical relationships. This can be further explored through examination of the regression exponent (p, a) and coefficient (q, b) values (e.g., Harvey, 1997).

For the fan area vs. catchment area analysis, the 0.003 p and 0.342 q values suggest that fan area is undersized compared to catchment area, falling outside of the $p = 0.14$–2.9 and overlapping marginally with the lower range of q values (0.33–0.66) cited from other tributary junction fan studies (e.g., Crosta and Frattini, 2004; Al-Farraj and Harvey, 2005). The p and q values are commonly considered to be a function of fan history, catchment lithology and space for fan sedimentation (e.g., Hooke and Rohrer, 1977; Lecce, 1991; Harvey, 1997).

For the fan gradient vs. catchment area analysis, the 0.021 a and $-0.196\ ^{b}$ values suggest that the fan catchment areas are producing lower-than-expected fan gradients, falling outside of the $a = 0.091$ to 0.22 and overlapping marginally with the $b = -0.12$ to -0.21 ranges of other tributary-junction fan studies (Crosta and Frattini, 2004; Al-Farraj and Harvey, 2005). The a and b values are often associated with lithology, depositional processes, and base-level change controls (Harvey, 1997).

5.2. Catchment relief, gradient, and length vs. fan area and gradient

Analysis of catchment relief, gradient, and length has previously shown that fan- generating catchments have higher relief, longer lengths, and lower gradients than nonfan-generating ones (Section 4.1: Fig. 7). Morphometric analysis of the fan generating catchment relief, gradient, and length characteristics allows further exploration of fan area and gradient relationships.

The visual appearance of the regression plots suggests (i) a positive relationship between fan area and catchment relief (Fig. 13C), fan gradient and catchment gradient (Fig. 13F), fan area and catchment length (Fig. 13G); and (ii) a negative relationship between fan area and catchment relief (Fig. 13D), fan gradient and catchment gradient (Fig. 13E), and fan gradient and catchment length (Fig. 13H). However, the correlation coefficients continue to show weak relationships and in this instance with variable statistical significance (Table 4).

The strongest (but still weak) relationship (Table 4) relates to fan area vs catchment length, with longer catchments creating larger fans. Other studies of tributary fans (e.g., Al-Farraj and Harvey, 2005) suggest

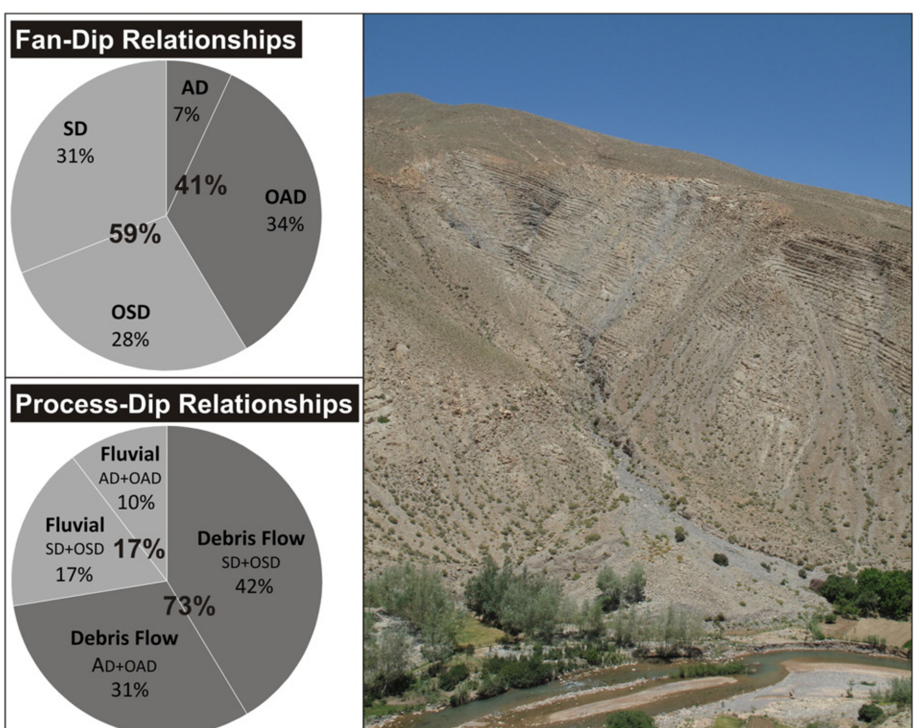


Fig. 12. Tributary fan and bedrock dip/process relationships. AD = anti-dip; OAD = oblique anti-dip; SD = syn-dip; OSD = oblique syn-dip; DF = debris flow; F = fluvial. Photo shows an example of a debris flow syn-dip tributary fan (fan 10: Table 3).

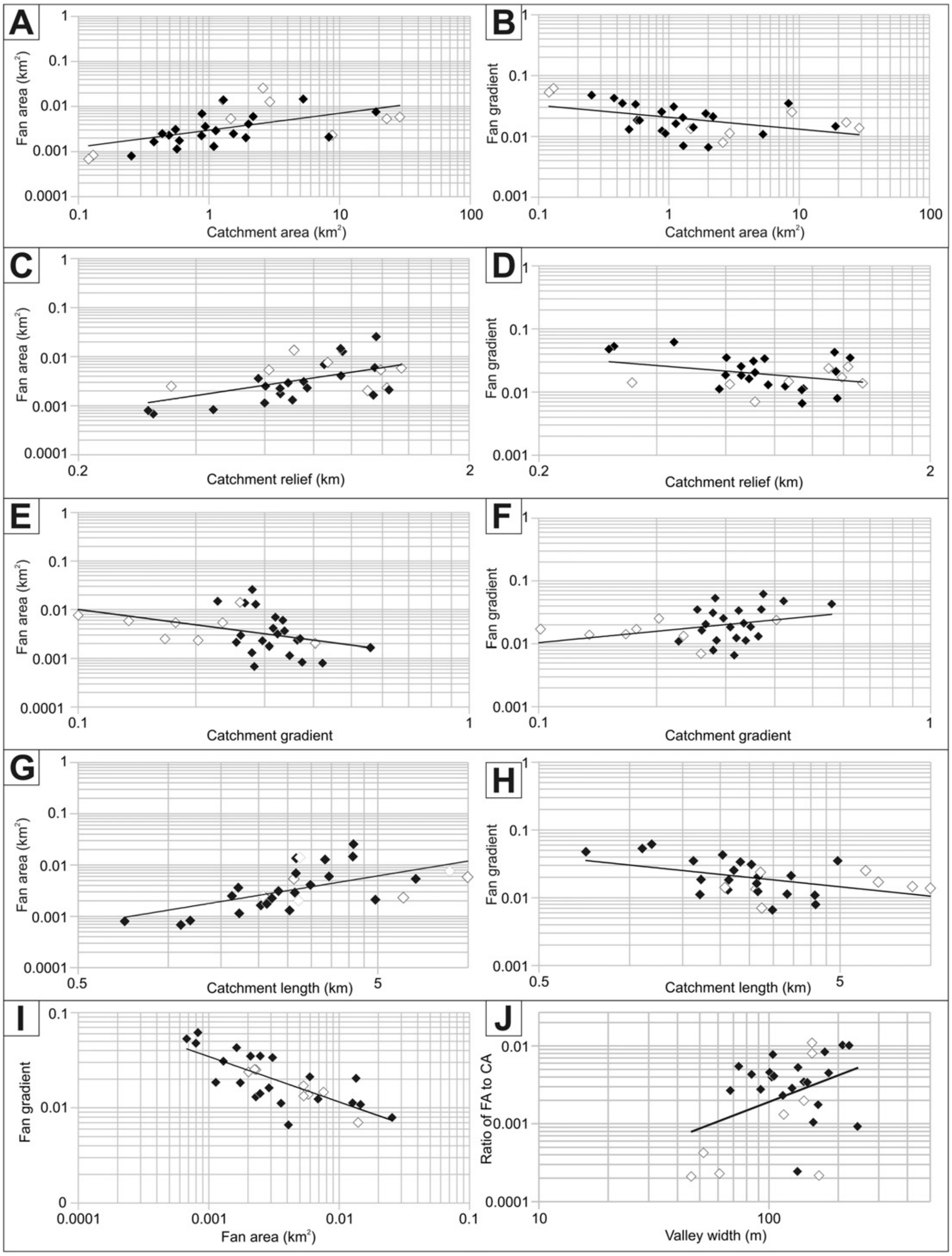


Fig. 13. Morphometric relationships of (i) fan and catchment (A–H); (ii) fan area and gradient (I); and (iii) fan area/catchment area ratio and valley width (J) variables.

Table 4
Results of regression analyses and their statistical significance for catchment, tributary-junction fan, and trunk valley variables.

Dependent vs. independent variables	Regression equations	R^2	Standard error	Significance *p* values
Fan area vs. catchment area	$F = 0.003\ A^{0.342}$	0.267	0.811	0.04
Fan gradient vs. catchment area	$G = 0.021\ A^{-0.196}$	0.209	0.540	0.013
Fan gradient vs. catchment relief	$G = 0.017\ S^{-0.5}$	0.144	0.571	0.073
Fan gradient vs. catchment gradient	$G = 0.042\ S^{0.585}$	0.199	0.570	0.067
Fan gradient vs. catchment length	$G = 0.030\ S^{-0.46}$	0.200	0.543	0.015
Fan area vs. catchment relief	$F = 0.005\ S^{1.103}$	0.235	0.829	0.08
Fan area vs. catchment gradient	$F = 0.001\ S^{-0.95}$	0.130	0.884	0.055
Fan area vs. catchment length	$F = 0.001\ S^{0.881}$	0.308	0.788	0.02
Fan gradient vs. fan area	$G = 0.001\ F^{-0.466}$	0.533	0.415	0
Ratio of FA/CA vs. valley width	$y = 0.00001\ x^{1.13}$	0.152	1.144	0.037

similarly weak (to moderate) relationships between fan morphology and catchment relief, gradient, and length.

5.3. Fan area vs. fan gradient

The analysis of fan and catchment morphological variables is a standard approach for alluvial fan research (Harvey, 1997). However, variables of fan morphology can also be analysed by regression. Plotting fan area against fan gradient shows a clear negative visual relationship (Fig. 13I) where larger fans are associated with lower gradients. This analysis shows the strongest correlation coefficient and statistical significance (Table 4).

Fan area vs. fan gradient relationships are commonly explained by sedimentary processes where debris-flow fans typically are characterised by small areas and steep gradients contrasting with larger and less steep fluvial fans (e.g., Harvey, 1997). This appears to be the case for this study, although the absence of a very strong relationship warrants further consideration (see Sections 6 and 7).

5.4. Fan and catchment area ratio vs. valley width

Valley width provides the space for tributary-fan sedimentation, with wider valleys offering greater potential for fan building, contrasting with confinement by narrower valleys that provide more opportunity for tributary-fan interaction with the trunk drainage (toe trimming or complete removal; e.g., Wang et al., 2008). Simple visual analysis of fans and valley widths (Section 4.2) shows fan distribution across the full range of valley widths (Fig. 8A). However, this approach does not take into consideration fan size in relation to valley width. This can be explored using the ratio of fan to catchment area and plotting them against valley width. This analysis generates a weak positive, but statistically valid relationship (Fig. 13J; Table 4) suggesting that fan size increases with valley width, confirming a valley confinement influence on fan building.

6. Residual analysis

The analysis of residuals (deviations from the predicted best fit line) from the fan and catchment regression is an approach that can be used to further explore fan morphology (e.g., Harvey, 2002b; Al-Farraj and Harvey, 2005). The approach uses the regression analyses for fan area and gradient against catchment area (Table 4).

The residual plots reveal that the tributary fans are smaller and of lower gradient than predicted, and these occur in three main groups (Fig. 14A): (i) small-steep fans, (ii) small low gradient fans, and (iii) large low gradient fans, with a notable absence of large steep fans. When the groups are considered in terms of sedimentary process (Fig. 14B), it seems that debris flow fans dominate the small-steep group and fluvial fans tend to plot in the lower gradient groups. When rock strength is considered, catchments dominated by weak bedrock tend to relate to small-steep fans (Fig. 14C) that are those dominated by debris flow processes (Fig. 14B). In contrast, catchments dominated by strong or intermediate bedrock plot in the lower gradient groups, with a higher proportion of fluvial fans. Rock strength also influences the trunk valley and catchment morphologies. This is especially the case in canyon settings where canyons produce a confined space for fan development and markedly stepped stream profiles within lower parts of the catchments in close proximity to the canyon walls, often suppressing sediment supply. Fans that form in confined valley settings occupy the ‘small area’ groupings (Fig. 14D), suggesting that valley width has some confinement control on limiting sediment supply. Bedrock lithology also has a passive configuration influence concerning the dip of the bedrock with respect to the catchment and trunk valley. Anti-dip fans dominate the lower gradient groups, whilst syn-dip groups dominate the smaller area groups (Fig. 14E).

Although the residuals are distributed into three broad groups, notable outliers occur such as fan 13 (Fig. 14A). This fan is a very large and low gradient form and is unique in that it is incised into a relict Quaternary fan (Fig. 4E) and is reworking the relict fan sediment into the modern fan. This forms a substantial area of extensive fan backfilling and storage (Fig. 7). A group of four fans (Fig. 14A) are additional large and low gradient outliers, but these have no clear explanation beyond speculation, warranting further exploration beyond the scope of this research. Explanations could relate to a large landslide that is found in the catchment area of fan 4, whilst fan 17 has considerable human modification as it occupies the main route into the village of Tizguin.

7. Discussion

7.1. Fan vs. nonfan-catchment characteristics

Factors that control the absence or generation of tributary-junction fans have been considered by previous authors (e.g., Gómez-Villar et al., 2006; Wang et al., 2008). These studies highlight the role of catchment morphological and geological characteristics for generating tributary-junction fans. This study shows similar relationships. Morphologically, the studied tributary catchments show that fan-generating catchments have higher relief, longer lengths, lower gradients, and larger areas. Whilst geologically, the fan-generating catchments typically comprise weaker bedrock, have greater catchment sediment storage, and are more commonly configured to the gentler fold limb of the regional syncline.

Catchment morphological characteristics are considered important for sediment yield to construct alluvial fans (Oguchi and Ohmori, 1994). In this study relief and area thresholds for sediment yield are evident, where tributary-junction fans are more commonly created when catchment relief is >578 m and area is >0.88 km^2. However, an upper catchment area threshold value is apparent where catchment areas above 28 km^2 do not create tributary-junction fans. These larger catchments have evidence for greater upstream catchment sediment storage capacity, and they would also possess a better ability to generate larger flood discharges that prevent fan formation upon interaction with the high discharges of the trunk River Dades. Similar catchment area size values and threshold relationships for tributary junction alluvial fan formation have been recorded by Wang et al. (2008).

Catchment geological characteristics primarily relate to lithology where weaker bedrock such as mudstone is considered to be more erodible with higher sediment yield potential (e.g., Bull, 1962). In this study, catchments dominated by weak strength bedrock generate sufficiently large sediment yields to construct a tributary-junction fan. Such bedrock, particularly characterised by the Ouchbis Formation, tends to have a better-developed and more closely spaced discontinuity pattern, meaning a greater likelihood of weathering and the development of much denser catchment drainage network (Hooke and Rohrer, 1977; Calvache et al., 1997). This elevated catchment erodibility in turn forms larger catchment areas and a greater potential for higher sediment yields and thus enhanced alluvial fan development. Evidence for high sediment yield within the fan-generating catchments can be seen from areas of tributary valley floor sediment coverage. These storage areas are coincident with valley sides comprising weak and intermediate strength bedrock. The hillside sediment supply occurs by shallow translational mass movements along bedding planes that dip into the tributary channel streams. This arrangement is an effective hillslope-channel coupling configuration (Harvey, 2002a) that enhances sediment supply into stream channels (Weissel and Seidl, 1997). The bedrock dip is related to the large fold structures of the study area (Fig. 2), and catchments that form tributary junction fans are dominantly associated with gentler fold limbs. The morphological development of alluvial fans associated with actively growing fold structures has been considered by Bahrami (2013). However, in terms of this study the structural control is considered to be tectonically passive where the fold structure simply

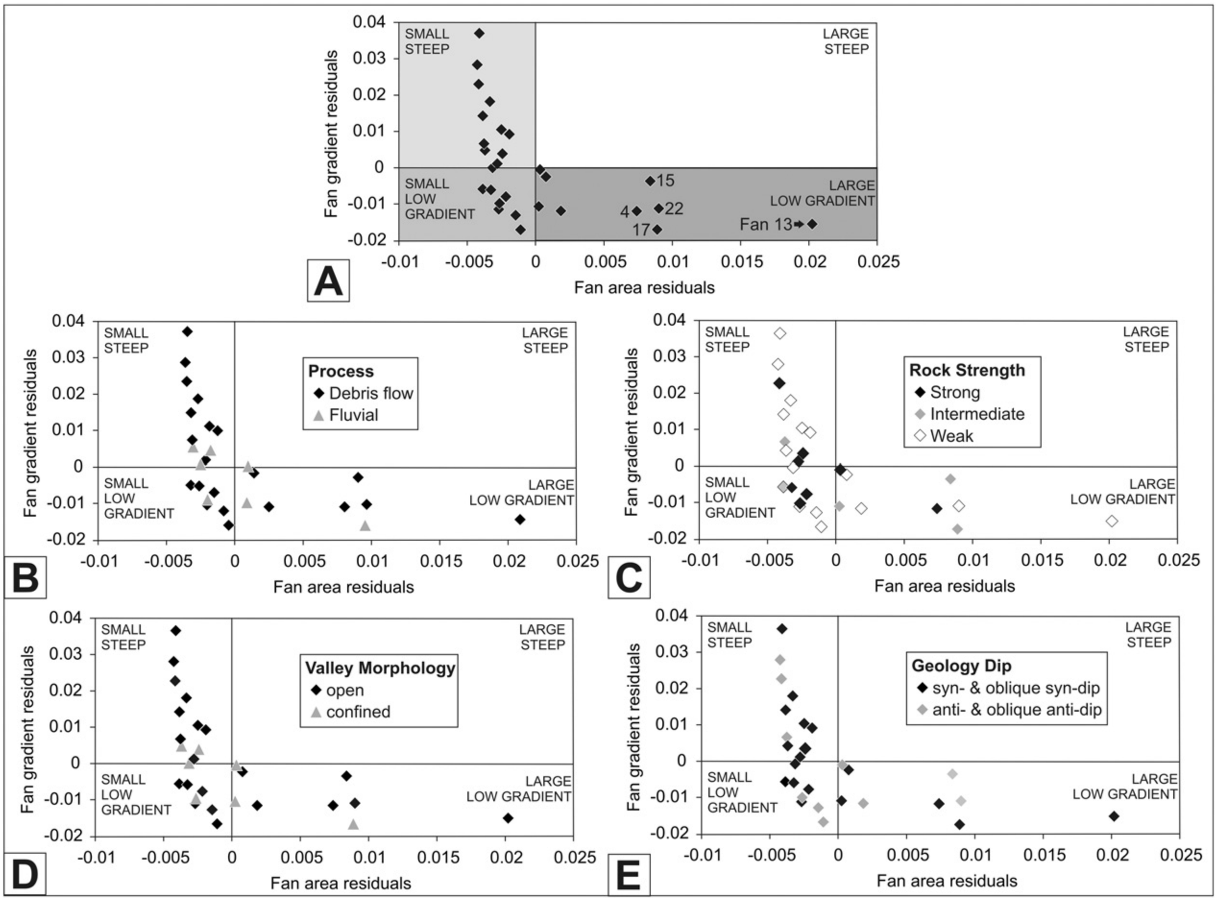


Fig. 14. Residual plots derived from morphometric analyses: (A) all data; (B) fan processes; (C) catchment rock strength; (D) trunk valley morphology, and (E) bedrock geology dip.

provides catchment gradients (syn-dip vs. anti-dip) that enhance or limit catchment morphological characteristics and sediment supply. Further hillslope sediment supply is derived from large landslide complexes that occur within some of the catchments that generate tributary fans. These too appear to have some relationship to the regional bedding plane dips associated with the regional fold structures, but unlike some tributary fan studies (e.g., Crosta and Frattini, 2004) their impact upon sediment supply and tributary fan formation relationships are unclear and warrant further investigation beyond the scope of this study. Hillslope sediment supply and valley floor sediment storage is most commonly located in the most distal (downstream) parts of the fan-generating catchments meaning that sediment is ready to be supplied to the fan when a flood event occurs.

7.2. Trunk valley controls on tributary-junction fan development

Key studies of tributary-junction alluvial fans comment upon the importance of the confinement setting of the valley into which the tributary-junction fan can build (e.g., Gómez-Villar et al., 2006). Valley width limits the space for fan progradation (Gómez-Villar et al., 2006), whilst the trunk drainage stream power will influence storage or reworking of tributary sediment (Bull, 1979; Wang et al., 2008). This study also suggests that valley width and particularly the proximity of the trunk river channel to the tributary junction are key controlling factors for fan development, especially in confined valley settings. The River Dades normally occupies a limited width of the valley floor reflecting the perennial low flow discharge conditions typical of the semiarid mountain setting of the study area along the NW margins of the Sahara. Flooding of the entire valley floors is exceptionally rare apart from within the confined canyon settings (widths <79 m) during the winter rainfall and higher altitude snowmelt periods. Tributary fans within these canyons (e.g., fan 1) are smaller and display trimming suggesting that these confined reaches, with their higher stream powers, have a greater ability to rework the high sediment yields supplied by the tributaries. Indeed, several tributary fans associated with canyons may have temporarily blocked the trunk valley (e.g., fan 28) before being breached and re-worked by the River Dades, a phenomenon that has been reported from other tributary-junction fan studies following low frequency and high magnitude dryland flood events (Schick and Lekach, 1987). During regular field visits to the study area since 2004 a number of floods have passed through the study area, typically during winter. These floods have had little impact upon the tributary fan shapes/morphologies, although some minor changes associated with incision/aggradation on the fans themselves and some minor distal fan erosion in confined canyon settings have been noted. This is supported when observing different time series of Google Earth imagery of the study area.

7.3. Tributary-junction fan morphological relationships

Studies of tributary-junction fans clearly highlight the importance of catchment properties for (i) generating fans, (ii) influencing fan processes, and (iii) controlling fan morphological properties (Crosta and Frattini, 2004; Al-Farraj and Harvey, 2005; Gómez-Villar et al., 2006; Wang et al., 2008). In this study the relationships between morphometric properties of the catchment and fan, as well as the processes that build the fans, appear to be apparent on a visual/qualitative basis but less clear from quantitative analysis.

The visual qualitative relationships show that the tributary-junction fans are typically small and steep and mainly built from debris-flow processes. Tributary fans dominated by fluvial processes were less common, but these were on the whole larger and of lower gradient that the debris-flow fans (Fig. 10B). These relationships are related to the strength and dip of the catchment bedrock geology, especially for fans dominated by debris-flow processes which are related to catchments dominated by weak bedrock with sediment supply enhanced by bedding planes that dip with the drainage gradient. These kinds of process-morphological relationships have been observed in several Quaternary and modern fan studies from confined and unconfined settings in a range of climatic settings (e.g., Harvey, 1997; Levson and Rutter, 2000; Crosta and Frattini, 2004).

Quantitative analysis of morphometric properties through regression reveals (i) weak positive relationship between catchment area and fan area and (ii) a weak negative relationship between catchment area and gradient. Although these morphological relationships are weak, they are statistically valid and are inkeeping with alluvial fan research (e.g., Harvey, 1997). Process-form relationships are normally strong for alluvial fans (Harvey, 1997); but here they are lacking, or where present, are very weak at best (Fig. 13). The only relationships appear to relate to lower catchment gradients (Fig. 13E, F) and longer catchment lengths (Fig. 13G, H) which seem more likely to form fluvial fans that possess larger fan areas and lower fan gradients. The absence of process-form relationships could be related to sample size or preservation issues associated with tributary fans.

Analysis of the regression exponents, coefficients, and residuals (Figs. 12 and 13) suggests that the tributary fans are smaller and lower gradient than expected. This could be explained by a combination of catchment and trunk valley controls.

Catchment controls: The formation of smaller and lower gradient than expected tributary fans could be explained by sediment type (size/composition) and yield in relation to catchment rock strength, storage, and throughput. Weak bedrock dominates the tributary fan catchments, and this seems to be important for producing small-steep debris-flow-dominated fans according to the residual plot distributions (Fig. 14B, C). In contrast, intermediate-strong bedrock tends to form lower gradient fluvial fan forms (Fig. 14). These rock strength and process observations are in-keeping with numerous studies of fan process and catchment lithology (e.g., Harvey, 1997). This potential for tributary sediment yield is further evident from catchment storage, with some 48% of fan-generating catchments showing evidence for storage (Table 3). Most of the sediment storage areas are in lower catchment reaches and directly connected to the fans (Fig. 7), enhancing fan sediment supply. However, fans dominated by strong limestone bedrock in lower parts of their catchments have canyon reaches (e.g., fans 1 and 28) where morphological (knickpoints) and sedimentological (boulder jams) bottlenecks occur, suppressing weaker strength sediment yield from upstream.

Trunk valley controls: the formation of tributary fans that are smaller and lower gradient than expected could be explained by trunk valley confinement and interaction of the tributary sediment yield with the trunk drainage flow. Although fan size increases with valley width (Fig. 14J) suggesting confinement control (e.g., Gómez-Villar et al., 2006), the fans are clearly undersized; and this relates to a combination of confinement and how this influences the proximity and behaviour of the trunk drainage. Either the fans are (i) building to the space available but are then being eroded due to the proximity of the trunk drainage, (ii) the fans are never building to their optimum size for the space available because of consistent trunk drainage erosion, or (iii) a combination of (i) and (ii). Fan shapes suggest that interaction between the tributary and the trunk drainage is a common occurrence, especially within the more highly confined canyon settings. In less-confined settings, the fans have space to prograde, but this is dependent upon the tributary fan catchment yield and interaction with the trunk drainage flow. It is probable that the fans are still evolving and will adjust their size or gradient through time to fit the regression predictions. However, the time scale in relation to fan history is significant here. The tributary fans are located within a trunk drainage that has a complex, longer-term climate (sediment supply) and tectonic (base-level lowering) history over the Plio-Quaternary (Stokes et al., 2008; Boulton et al., 2014). However, the tributary fans show little evidence for long time scale dynamics, lacking the complex inset surfaces described by many Quaternary fan studies (e.g., Silva et al., 1992). Large Quaternary fan forms are evident in the study area (Fig. 4E), but they are abandoned relict features, whose surfaces now form parts of tributary fan catchment areas. Thus, the fans are modern or Holocene at best features whose dynamics are more closely linked to the contemporary climate and flood regime variability patterns.

7.4. Tributary-junction fan build and reset model

The weak morphometric characteristics of the tributary fans and their catchment areas suggest interplay between the tributary catchments and the trunk valley Dades River. Clearly, tributary catchments of a certain size, relief, and gradient that are dominated by weak bedrock geology with a syn-dip configuration are the most prone to supplying sufficient sediment to a tributary junction for fan development, agreeing with other tributary fan studies (e.g., Gómez-Villar et al., 2006; Wang et al., 2008). Tributary fan building will only occur where interaction with the trunk drainage is minimal (e.g., Wang et al., 2008). For the River Dades interactions are more likely in confined canyon settings dominated by strong bedrock and less common in wider, more open valley settings dominated by weak bedrock.

The catchment-trunk valley morphological–geological relationships are important for providing the landscape framework conducive for tributary-junction fan formation; however, fan development further depends upon tributary and trunk drainage flood regime that are controlled by the precipitation and flood regime variability of the desert-mountain climate that typifies the southern-central High Atlas. Here, precipitation is normally associated with three weather systems: (i) winter-spring storm tracks from the Mediterranean, (ii) summer-autumn storms from south of the Sahara, and (iii) rare low pressure troughs from the Atlantic (Knippertz et al., 2003). The fluvial response to these weather systems is variable but typically dominated by annual winter–spring occurrences (Schulz et al., 2008). These include sustained precipitation and snowmelt in high elevation (2–4 km) catchment locations providing a steady but diminishing perennial discharge along the Dades River (Schulz and de Jong, 2004; Schulz et al., 2008; Dłużewski et al., 2013). Winter–spring precipitation also generates frequent localised storms throughout the Dades catchment that activates the ephemeral tributary streams (Dłużewski et al., 2013) providing some flow contribution to the perennial Dades River. Less common, but of more significant geomorphic impact, are the rare precipitation events that occur on decadal or longer time scales linked to the incursions of Atlantic troughs (Knippertz et al., 2003). These regional weather systems activate entire catchments, generating flow in the normally ephemeral tributaries and highly elevated flood discharges through the perennial Dades River (Fink and Knippertz et al., 2003; Schulz et al., 2008; Dłużewski et al., 2013).

The interplay between the ephemeral tributaries and the perennial River Dades in the study area is presented in Fig. 15, providing an important insight into the spatial and temporal variability of tributary-junction fans and their role in coupling/connectivity within sediment-geomorphic systems. Perennial flow in the River Dades remains low for prolonged periods, with annual snowmelt and groundwater sustaining the low flow conditions in the arid climate. These climate and discharge relationships result in limited annual geomorphic activity by the River Dades in the trunk valley. In contrast, the ephemeral tributary catchments can be activated by the localised winter storms resulting in tributary fan building but only from catchments with the appropriate geological, morphological, and sediment supply conditions. Tributary fan building proceeds over subsequent years with limited interaction with the low flow River Dades. During the rare (>10 year) regional Atlantic trough events, the entire catchment becomes active. The elevated discharge in the River Dades results in valley bankfull widths that

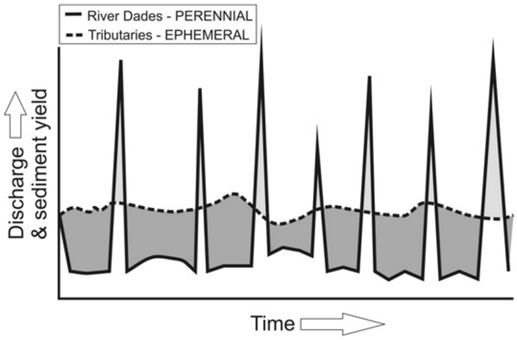


Fig. 15. Tributary-junction fan build and resent conceptual model. See text for explanation.

remove/rework tributary fans. Waning and post-flood periods from these large events would then allow the ephemeral tributary fans to rebuild until reset by the next regional low frequency, high magnitude event. This 'build and reset' conceptual model explains the morphometric residual pattern of small and low gradient fans, where fans are not able to build to their equilibrium size (area) and surface gradient with respect to the catchment characteristics because of resetting by the trunk valley drainage. This model is a conceptual one and warrants further exploration including more detailed analysis of climate and flood hydrology data, along with detailed field survey of the fans immediately following a >10 year flood event that resets the trunk valley. Schick and Lekach (1987) described a similar situation from the hyperarid Sinai Desert in Israel, but based only on the study of a single ephemeral tributary-junction fan that blocked its ephemeral trunk valley, building a lake upstream which subsequently failed. Our study complements and contrasts with that of Schick and Lekach (1987) by (i) providing a greater spatial perspective of tributary-junction fan building through analysis of a larger area that includes many fan, and nonfan-generating tributary catchments and by (ii) providing a different climate and more marked topographic perspective where ephemeral tributary streams interact with perennial trunk drainage in a higher relief setting.

Finally, although the model is based upon recent climate-discharge observations from the study area, the concept is probably valid for the Holocene and Pleistocene interglacials, acknowledging that climate-related humidity–aridity variations occurred and that these would impact upon flood discharge frequency and magnitude variations. A very different climate-flood discharge-sediment yield relationship would exist between the tributaries and trunk drainage during the Pleistocene glacials when excess sediment supply appears to have created coeval large tributary fans (Fig. 4E) and extensive valley floor aggradation.

8. Conclusions

Analysis of 186 tributary catchments to the River Dades in the distal part of the fold-thrust belt region of the High Atlas Mountains orogenic system has shown tributary junction alluvial fans are only generated from 29 (16%) of the catchments. Morphologically, these fan-generating catchments have higher relief, longer lengths, lower gradients, and larger areas than nonfan-generating catchments with clear lower and upper threshold values. Whilst geologically, the fan-generating catchments are dominated by weak bedrock with tributary channel sediment supply and storage enhanced by fold-limb related dip of the bedrock geology. The tributary fans primarily build by debris-flow processes either into open valleys where they possess a lobate morphology or confined canyon settings where fans are commonly trimmed by the River Dades. The trunk drainage valley morphology is a function of rock strength, with strong limestone-dominated bedrock-forming canyons whose stepped canyon wall morphology can suppress tributary drainage development and sediment supply to the trunk drainage and tributary fan. Morphometric analysis of catchment (area, relief, length, gradient), tributary fan (area, gradient, process), and trunk valley (width) variables reveals weak relationships, highlighted by residual analysis that shows a dominance of fans with undersized areas and lower than expected gradients. These relationships can be explained by integration of (i) catchment bedrock geology in terms of rock strength, structure and storage, (ii) trunk drainage valley morphology, width and proximity of the perennial River Dades to the ephemeral fan building tributary junctions, and (iii) the local and regional climate variability and its relationship to tributary stream and trunk drainage flood regime. Collectively these manifest in a build and reset model where tributary fans build progressively during annual winter–spring storm events until they are reset by rare large floods by the River Dades. The climate, rock strength, and morphological controls mean that the fans are attempting to build towards an equilibrium form but never achieve through a combination of trunk valley resetting and catchment sediment yield variability, providing important insights into sediment-geomorphic system coupling/connectivity.

Acknowledgements

Fieldwork for this research was partly supported by a National Geographic research grant (8609-09). Fieldwork support was provided by Alaeddine Belfoul, Farid Faik, and Sophia Bouzid (Ibn Zohr University, Agadir). We thank three anonymous reviewers and Richard Marston for their constructive comments and editorial help.

References

Agence Nationale de la Conservation Fonciè, du Cadastre et de la Cartographie (ANCFCC), 1997. 1:40,000 Black and White Aerial Photographs May 1996–August 1997 (Rabat, Morocco).
Al-Farraj, A., Harvey, A.M., 2005. Morphometry and depositional style of Late Pleistocene alluvial fans: Wadi Al-Bih, northern UAE and Oman. In: Harvey, A.M., Mather, A.E., Stokes, M. (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London, Special Publications 251, pp. 85–94.
Bahrami, S., 2013. Tectonic controls on the morphometry of alluvial fans around Danehkhoshk anticline, Zagros, Iran. Geomorphology 180–181, 217–230.
Beauchamp, W., Allmendinger, R.W., Barazangi, M., Demanti, A., El Alji, M., Dahmani, M., 1999. Inversion tectonics and the evolution of the High Atlas Mountains, Morocco, based upon a geological–geophysical transect. Tectonics 18, 163–184.
Boulton, S.J., Stokes, M., Mather, A.E., 2014. Transient fluvial incision as an indicator of active faulting and Plio-Quaternary uplift of the Moroccan High Atlas. Tectonophysics 633, 16–33.
Bull, W.B., 1962. Relations of alluvial-fan size and slope to drainage basin size and lithology in western Fresno County, California. US Geological Survey Professional Paper 430Bpp. 51–53.
Bull, W.B., 1977. The alluvial fan environment. Prog. Phys. Geogr. 1, 222–270.
Bull, W.B., 1979. Threshold of critical power in streams. Geol. Soc. Am. Bull. 90, 453–464.
Calvache, M.L., Viseras, C., Fernández, J., 1997. Controls on fan development — evidence from fan morphometry and sedimentology; Sierra Nevada, SE Spain. Geomorphology 21, 69–84.
Carte du Maroc 1968a. Tinerhir. 1:100,000.
Carte du Maroc 1968b. Zawyat Ahançal. 1:100,000.
Carte Géologique du Maroc 1990. Zawyat Ahançal. 1:100,000.
Carte Géologique du Maroc 1993. Tinerhir. 1:100,000.
Carte Géologique du Maroc 1985. Morocco map 1:1000,000. Notes and memoir, no. 260.
Crosta, G.B., Frattini, P., 2004. Controls on modern alluvial fan processes in the central Alps, Northern Italy. Earth Surf. Process. Landf. 29, 267–293.
de Jong, C., Cappy, S., Finckh, M., Funk, D., 2008. A transdisciplinary analysis of water problems in the mountainous karst areas of Morocco. Eng. Geol. 99, 228–238.
Dewey, J.F., Helman, M.I., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the western Mediterranean. In: Coward, M.P., Dietrech, D., Park, R.G. (Eds.), Alpine Tectonics. Geological Society, London Special Publication vol. 45, pp. 265–283.
Dłużewski, M., Krzemień, K., Rojan, E., Biejat, K., 2013. Stream channel development in the southern parts of the High Atlas Mountains, Morocco. Geografija 49, 10–21.
Fink, A.H., Knippertz, P., 2003. An extreme precipitation event in Southern Morocco in Spring 2002 and some hydrological implications. Weather 58, 377–387.
Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., El Azzouzi, M., Maury, R.C., Charrière, A., Taki, Z., Benammi, M., Michard, A., 2008. The atlas system. In: Michard, A., Saddiqi, O., Chalouan, A., Frizon de Lamotte, D. (Eds.), Continental Evolution: The Geology of Morocco. Structure, Stratigraphy and Tectonics of the Africa-Atlantic-Mediterranean Triple Junction. Lecture Notes in Earth Sciences vol. 116, pp. 133–202.
Gómez-Villar, A., Álvarez-Martínez, J., García-Ruiz, J.M., 2006. Factors influencing the presence or absence of tributary-junction fans in the Iberian Range, Spain. Geomorphology 81, 252–264.
Goudie, A.S., 2006. The Schmidt Hammer in geomorphological research. Prog. Phys. Geogr. 30, 703–718.

Harvey, A.M., 1997. The role of alluvial fans in arid zone fluvial systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands. Wiley, Chichester, pp. 231–259.
Harvey, A.M., 2002a. Effective timescales of coupling within fluvial systems. Geomorphology 44, 175–201.
Harvey, A.M., 2002b. The role of base-level change in the dissection of alluvial fans: case studies from southeast Spain and Nevada. Geomorphology 45, 67–87.
Hooke, R.L., Rohrer, R., 1977. Relative erodibility of source-area rock types, as determined from second-order variations in alluvial-fan size. Geol. Soc. Am. Bull. 88, 1177–1182.
Hughes, P.D., Fenton, C.R., Gibbard, P.L., 2011. Quaternary glaciation in the Atlas Mountains of North Africa. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Developments in Quaternary Science vol. 15. Elsevier, Amsterdam, The Netherlands, pp. 1065–1074.
Hughes, P.D., Fink, D., Fletcher, W.J., Hannah, G., 2014. Catastrophic rock avalanches in a glaciated valley of the High Atlas, Morocco: 10Be exposure ages reveal a 4.5 ka seismic event. Geol. Soc. Am. Bull. 126, 1093–1104.
Knippertz, P., Christoph, M., Speth, P., 2003. Long-term precipitation variability in Morocco and the link to large-scale circulation in recent future climates. Meteorog. Atmos. Phys. 83, 67–88.
Lecce, S.A., 1991. Influence of lithologic erodibility on alluvial fan area, western White Mountains, California and Nevada. Earth Surf. Process. Landf. 16, 11–18.
Leeder, M.R., Mack, G.H., 2001. Lateral erosion ('toe-cutting') of alluvial fans by axial rivers: implications for basin analysis and architecture. J. Geol. Soc. Lond. 158, 885–893.
Levson, V.M., Rutter, N.W., 2000. Influence of bedrock geology on sedimentation in Pre-Late Wisconsinan alluvial fans in the Canadian Rocky Mountains. Quat. Int. 68–71, 133–146.
Medina, F., Cheraoui, T.-E., 1991. Focal mechanisms of the Atlas earthquakes, and tectonic implications. Geol. Rundsch. 80, 639–649.
Michard, A., 1976. Éléments de géologie marocaine. Notes Mém. Serv. Géol. Maroc 252 (408 pp.).
Oguchi, T., Ohmori, H., 1994. Analysis of relationship among alluvial fan area, source basin area, basin slope and sediment yield. Z. Geomorphol. N.F. 38, 405–420.
Schick, A.P., Lekach, J., 1987. A high magnitude flood in the Sinai Desert. In: Myer, L., Nasch, O. (Eds.), Catastrophic Flooding. Allen and Unwin, Boston, pp. 381–409.
Schulz, O., de Jong, C., 2004. Snow melt and sublimation: field experiments and modelling in the High Atlas Mountains of Morocco. Hydrol. Earth Syst. Sci. 8, 1076–1089.
Schulz, O., Busche, H., Benbouziane, A., 2008. Decadal precipitation variances and reservoir inflow in the semi-arid Upper Drâa basin (South-Eastern Morocco). In: Zereini, F., Hötzl, H. (Eds.), Climatic Change and Water Resources in the Middle East and North Africa. Springer, Heidelberg, pp. 165–178.
Silva, P.G., Harvey, A.M., Zazo, C., Goy, J.L., 1992. Geomorphology, depositional style and morphometric relationships of Quaternary alluvial fans in the Guadalentin depression (Murcia, Southeast Spain). Z. Geomorphol. 36, 325–341.
Stokes, M., Mather, A.E., Belfoul, A., Farik, F., 2008. Active and passive tectonic controls for transverse drainage and river gorge development in a collisional mountain belt (Dades Gorges, High Atlas Mountains, Morocco). Geomorphology 102, 2–20.
Teixell, A., Arboleya, M.-L., Julivert, M., 2003. Tectonic shortening and topography in the central High Atlas (Morocco). Tectonics 22, 1–13.
U.S. Geological Survey (USGS), 2015. EarthExplorer. http://earthexplorer.usgs.gov/ (accessed 10/03/2015).
Wang, H., Harvey, A.M., Xie, S., Kuang, M., Chen, Z., 2008. Tributary-junction fans of China's Yangtze Three-Gorges valley: morphological implications. Geomorphology 100, 131–139.
Weissel, J.K., Seidl, M.A., 1997. Influence of rock strength properties on escarpment retreat across passive continental margins. Geology 25, 631–634.
Wells, S.G., Harvey, A.M., 1987. Sedimentologic and geomorphic variations in storm generated alluvial fans, Howgill Fells, northwest England. Geol. Soc. Am. Bull. 98, 182–198.